APPENDIX III. DUCT SEALING TECHNIQUES FOR LARGE COMMERCIAL BUILDINGS

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Ducts Sealing Techniques for Large Commercial Buildings

Introduction

Our duct leakage intervention study (described in Appendix II) showed that the energy impact of upstream and downstream duct leakage in large commercial buildings with variable-air-volume (VAV) HVAC systems can be substantial. Therefore, if duct systems in this large commercial building population are leaky, then it is important to have effective duct sealing methods that can be readily commercialized and applied.

As found, the one-year old test building that we studied in this project showed every indication of a "tight" thermal distribution system: good application of mastic, metal bands at joints, and overall high quality installation. We found that ducts both upstream and downstream of VAV boxes were sealed, with a total fractional leakage flow of about 5% at operating conditions. An example of the sealing detail was that mastic had even been applied to the inside of plenum takeoff joints, downstream of the VAV boxes.

We have also measured fractional leakage flows in four other California buildings (Xu et al. 1999, 2002). Two of the buildings were built in 1996 and had leakage fractions similar to the one-year old test building. However, the other two were much more leaky: one built in 1979 had a leakage fraction of about 17%; the other (built in 1989) had a leakage fraction of about 25%. The duct sealants used and their location in the four older buildings are not well documented, but we know that mastic was used on some duct joints in the building that was built in 1989.

Although this set of leakage flow data is very limited, it has two significant implications for California buildings:

1. The *tight* ducts are evidence that at least some HVAC contractors in the California building industry already know how to effectively seal ducts in new large commercial buildings, even though specifications for duct leakage airflows tend to be poorly defined for new construction (especially for the lower-pressure-class duct sections that are located downstream of VAV boxes).
2. The *leaky* ducts are evidence that the California building industry needs to consider sealing ducts in existing large commercial buildings. However, sealing ducts in existing buildings is more challenging than in new buildings, because of reduced access to ducts after ceiling panels are in place and spaces are occupied. Remote sealing techniques that reach duct leaks without having to access and seal every joint manually are preferable in these cases.

Over the past decade, Lawrence Berkeley National Laboratory has developed an internally applied aerosol-based technology to seal leaky ducts remotely. As a commercialized technology, contractors have actively used it to seal thousands of duct systems in houses and hundreds of duct systems in small commercial buildings. Since 1997, we have begun investigating how to apply similar technology in large commercial buildings (Modera et al. 2001, Carrie et al. 2002).

The aerosol sealing process involves the separate but simultaneous injection of carrier air and aerosol sealant into the duct system, with intentional duct openings (e.g., grilles, fans) blocked off and sensitive components isolated. An integrated fan and airflow meter connects to the duct system to provide and measure carrier airflow from the room to the duct system. A sealant injector is inserted into the duct system downstream of the carrier air injection point. The injector's sealant pump supplies room temperature liquid sealant[1] through tubing to the injector; a separate stream of heated compressed air mixes with the liquid sealant at the injector nozzle discharge. Sealant particles are produced by atomization and drying of the liquid stream exiting the injector nozzle. The carrier airflow transports aerosol sealant particles to the leaks, where the particles collide with leak edges, accumulate, and ultimately seal the leaks.

Continuously monitoring the duct wall pressure difference and carrier airflow allows one to continuously determine the duct effective leakage area (ELA_{25}) and sealing rate[2], and to track sealing progress. As leaks are sealed, the ELA_{25} decreases (duct flow resistance increases), the duct wall pressure difference increases, and the carrier airflow (exiting through the leaks) decreases. The sealing rate also decreases, because the particle transport in the carrier air decreases. Changes in these parameters also serve to identify problems. For example, sudden changes in duct pressure difference and airflow can indicate that a grille covering or isolation blockage has failed.

When the ELA_{25} is relatively small (with associated high duct wall pressure difference), or the sealing rate becomes low and stable, sealing should be terminated. For example, aerosol sealing in residential or light commercial duct applications is usually terminated when the duct wall pressure difference reaches 500 Pa, at which point the ELA_{25} is often between 10 to 20 cm^2. We expect that similar termination criterion would be used when sealing ducts in a large commercial building.

Applying the existing single-injector aerosol technology to seal ducts in large commercial buildings is problematic, because these duct systems are much larger and more complex than duct systems in residential and small commercial buildings. For example, a typical supply-air duct system in a large commercial building has a fan blowing air into a main trunk duct, with a VAV box connected to each trunk outlet; ducts downstream of each VAV box branch off to supply grilles. The result is that the large commercial supply duct systems are long (several hundred feet) and it is difficult to inject sealant efficiently from a single point all the way to leaks near the end of the duct system. In addition, there are sensitive components such as heater coils and backdraft dampers inside VAV boxes. To maintain their functionality, these components should not be exposed to aerosol sealant.

Consequently, to reduce the distance that sealant must travel from injection to leakage sites, and to avoid spraying sealant into VAV boxes, the aerosol-sealing technology needs to use two injection stages. One stage involves sealing the main trunk of the duct system with the primary air inlets to the VAV boxes closed and with multiple injectors located along the length of the duct. The other stage involves sealing the numerous duct branches downstream of the VAV boxes. Both these configurations mean that being able to seal

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[1] The sealant is a water-based vinyl-acetate polymer liquid adhesive, with a concentration of 120 μg of solid adhesive per mL of liquid.

[2] ELA_{25} is defined as the cross-sectional area of a perfect nozzle that would produce the same flow as the total measured airflow through the leaks (carrier airflow), but at a reference duct wall pressure difference of 25 Pa. The sealing rate is indicated by the reduction in ELA_{25} per unit time.

multiple sections simultaneously and being able to move injectors quickly from one injection site to the next would reduce the time required to seal the entire system.

The remainder of this appendix describes the development and laboratory testing of a mobile aerosol-sealant injection system (MASIS) that can use multiple injectors simultaneously to seal multiple duct sections. To help the reader understand the multiple injector system, we have included a description of the aerosol sealing technology. DOE funded the development of the injector.

The three key elements in the development and laboratory testing of MASIS were:

1. Develop protocols (plans) to seal ducts upstream and downstream of VAV boxes.
2. Refine injection system components for use in field applications.
3. Test the automated monitoring system that measures process pressures and airflows.

At the end of this appendix, we also discuss whether there is a need to develop field retrofit techniques for sealing duct system components such as VAV boxes and supply grilles.

Multiple-Injection Aerosol Sealing Technology

Technology Overview: We initially developed the mobile aerosol-sealant injection system as a laboratory prototype. Each aerosol injection station of MASIS consists of a cart with a liquid sealant tank, a peristaltic pump, and an electrical control box; a sealant tube attaches the pump to an aerosol sealant injector. A compressed air hose and electrical wiring for the injection heater are also attached to the injector.

Figure III-1 shows a schematic of the multiple injection system. Figures III-2 and III-3 show the cart and control box, as well as a schematic of the electrical circuitry in the control box.

Aerosol Sealant Injector Details: Figure III-4 shows an aerosol sealant injector; Figure III-5 illustrates the injector components schematically.

The aerosol injector stem is a copper pipe ($1^{3}/_{8}$ inch O.D.), which contains the liquid sealant line and the compressed air line with its electrical heater (110 V, 400 W). The top of the stem has a cap on which the injector nozzle is fastened. The purpose of the heater is to heat the compressed air so that it will evaporate the water in the atomized liquid sealant.

The injector nozzle is an external-mix atomizing nozzle (Model 970 S4, Düsen-Schlick GmbH). Figure III-6 shows a nozzle, and includes schematics that show the parts of the nozzle in more detail. Liquid sealant flows through the center of the nozzle’s liquid insert; heated compressed air flows between the air cap and the outside of the liquid insert. The inner diameters of the liquid insert and air cap discharges are 1.0 mm and 2.6 mm respectively; the liquid insert protrudes 1.2 mm from the air cap. The spray angle of the nozzle is 10 to 15 degrees; this small spray angle is important because it reduces the amount of sealant deposition on the duct walls and increases the sealing rate.

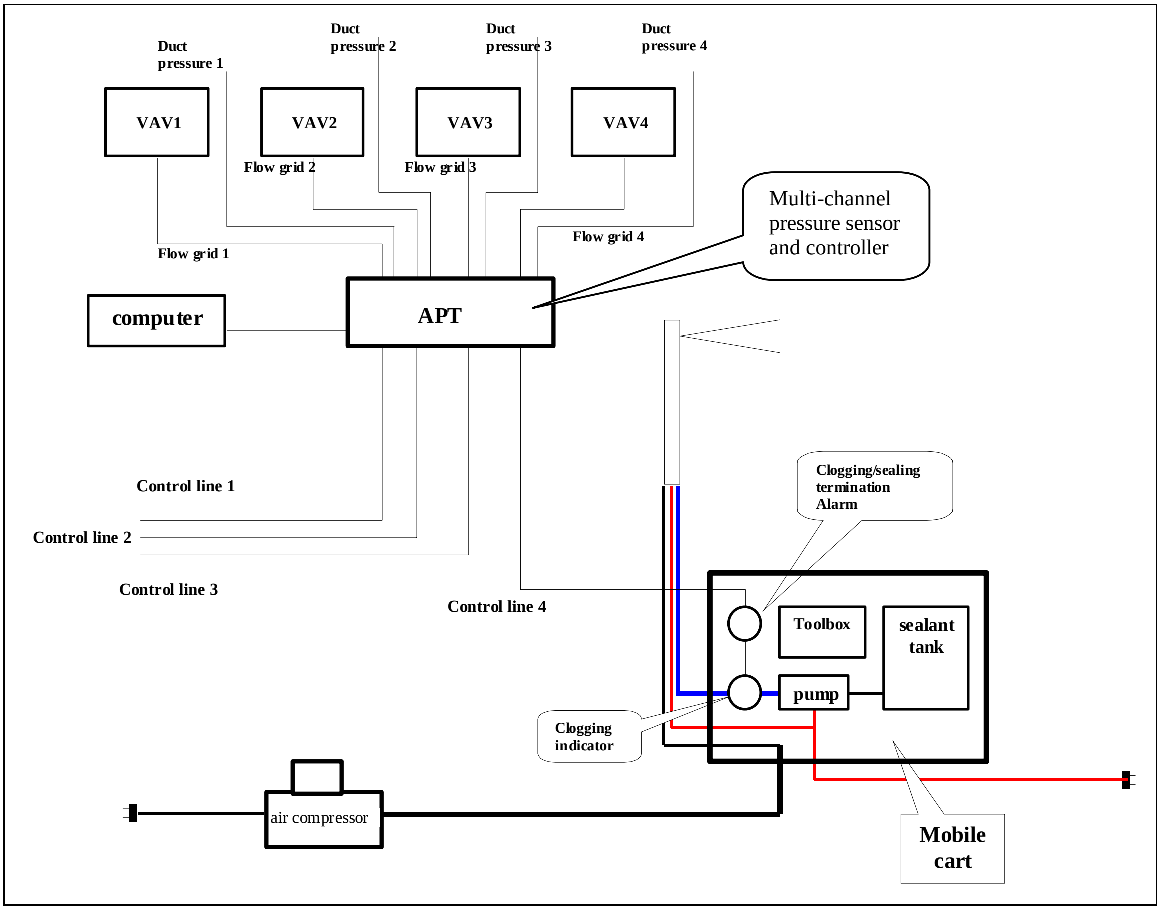

Figure III-1. Schematic of MASIS. This figure shows only one cart (lower right), but the schematic assumes that up to four injectors (each with a cart) could be used simultaneously, all controlled by a single computer.

Figure III-2. MASIS cart and injection system control box.

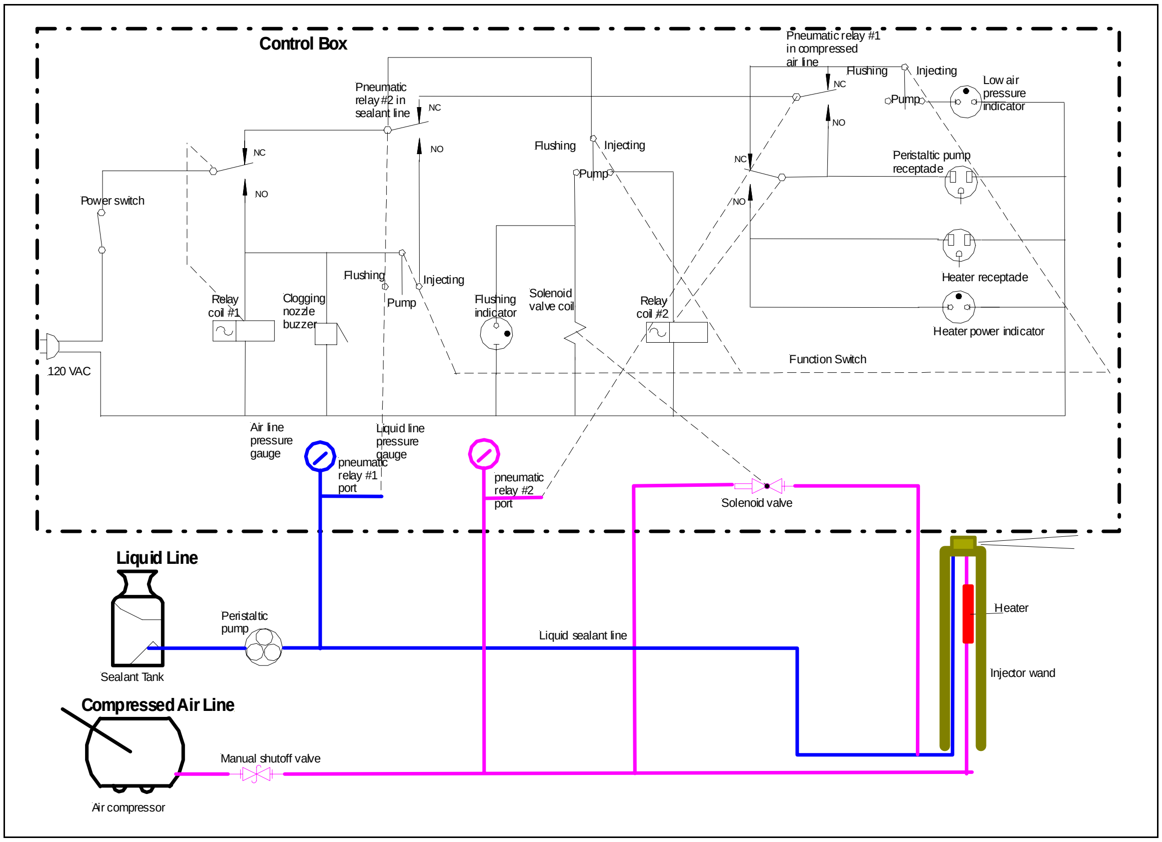

Figure III-3. Schematic of MASIS control box electrical circuitry, and connections to other injection system components.

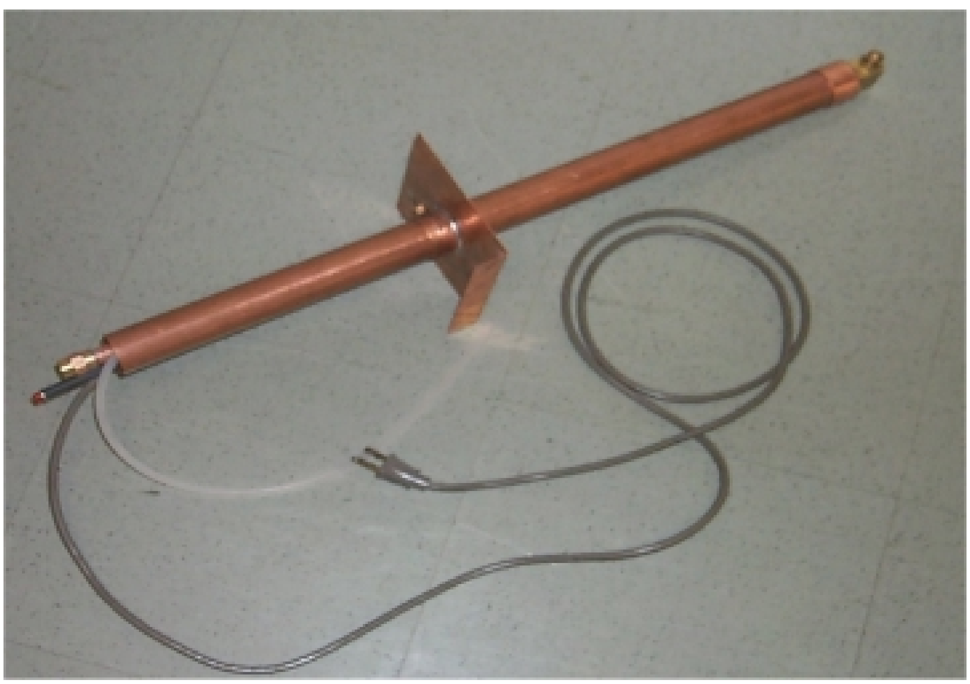

Figure III-4. Aerosol sealant injector.

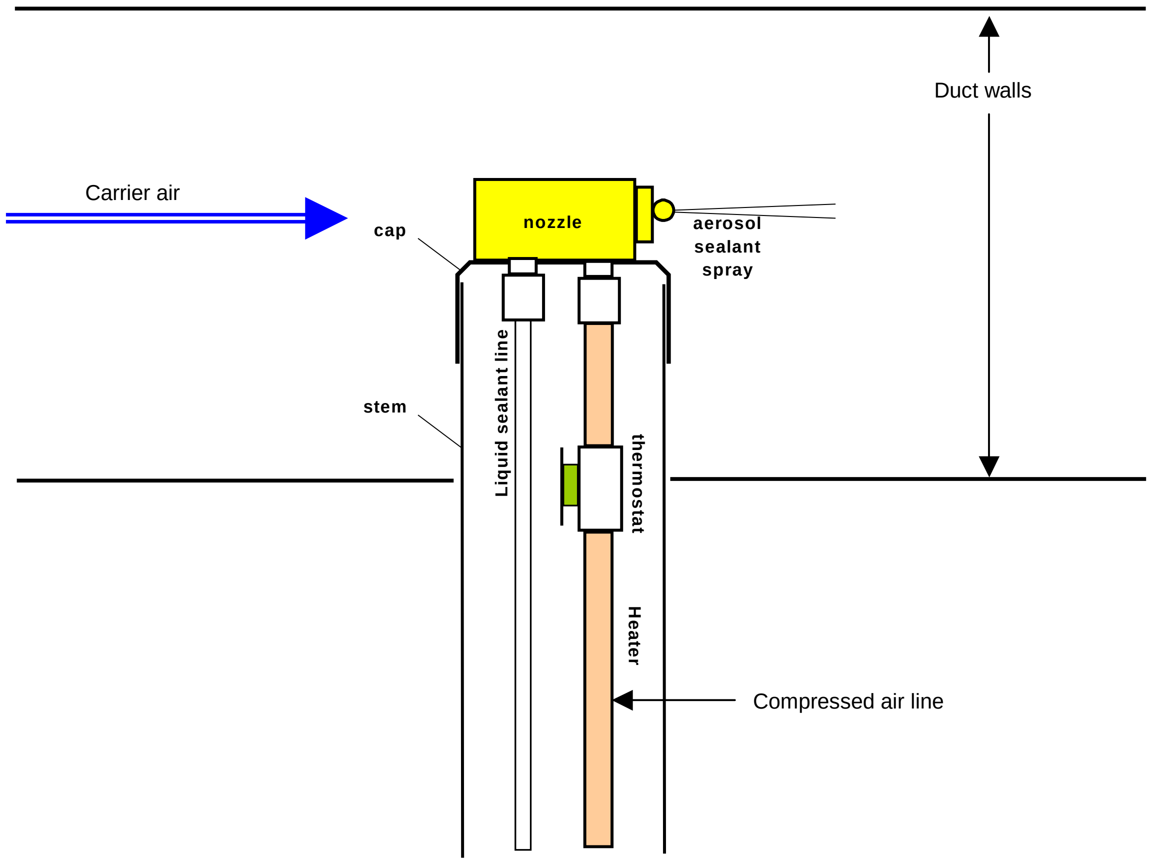

Figure III-5. Schematic of aerosol sealant injector, shown installed in a duct.

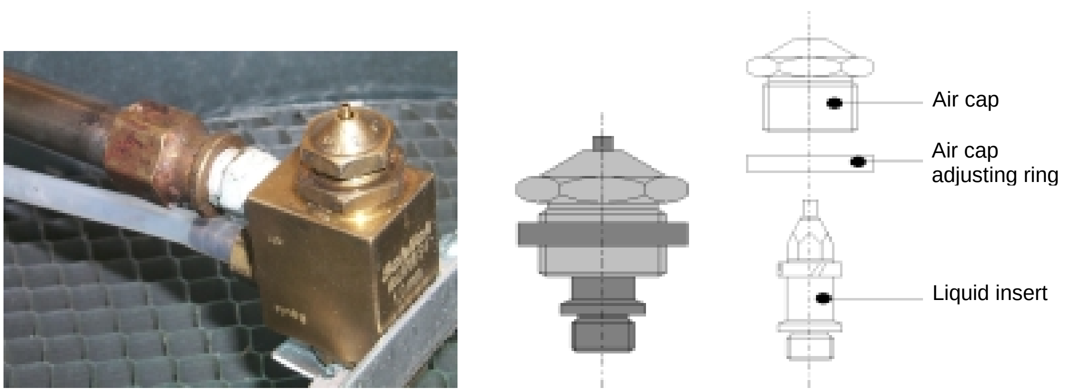

Figure III-6. Aerosol sealant injector nozzle, with schematics of components.

Site-Specific Planning for Duct Sealing

- Generate a duct map, which shows the location of all the VAV boxes and the location of all grilles associated with each VAV box.
- Develop a protocol to isolate the system fan and VAV boxes from the trunk; if the VAV box primary air dampers need to be closed manually, develop a protocol for that process.
- With assistance from the building engineer, identify and locate all sensitive components (e.g., smoke sensors, dampers); develop a protocol for protecting the components.
- Determine where and how to install the sealing fan with airflow meter.
- Determine how many aerosol injectors are needed and where to install them.
- Mark the locations of components requiring intervention or related to the sealing process (duct system and injection system) on duct map; also mark the related ceiling access panels.

Protocol for Sealing the Trunk Upstream of VAV Boxes

1. Turn off the system fan (if on) and isolate the system fan and VAV boxes from the system.
2. Protect sensitive components as needed.
3. Connect the sealing fan and airflow meter to the trunk system.
4. Setup the eight-channel Automated Performance Testing system (APT) and a computer to monitor the airflow and the duct wall pressure difference for the trunk duct.
5. Using the sealing fan with its airflow meter, determine the trunk ELA_{25}.
6. If the trunk is very leaky, inspect the trunk for large leaks and manually seal any that are found. Determine the ELA_{25} again if any sealing was carried out.
7. If further sealing is needed, install the aerosol sealant injectors. Otherwise, skip forward to the downstream sealing process.
8. Turn on all the injectors, monitor the duct wall pressure difference and carrier airflow changes, and continuously determine ELA_{25} as sealing proceeds.
9. Terminate the sealing once the trunk ELA_{25} stabilizes.

Protocol for Sealing Branch Ducts Downstream of VAV Boxes

Sealing multiple VAV branch ducts means there are multiple independent but simultaneous tasks. In this stage of the sealing process, MASIS can seal up to four branches at the same time. For each branch, all the associated grilles are temporarily covered and the associated primary air damper is opened. The sealing fan supplies the carrier airflow through the associated VAV box to the downstream leakage sites, and an aerosol injector injects sealant downstream of the box. The ELA_{25} of the branch duct is based on the airflow entering the associated VAV box (measured using the box flow grid); it is not based on the carrier airflow, which is the sum of the airflows supplied to the multiple downstream sections that are being sealed. The pressure difference across the duct wall is still measured in the trunk.

As part of this process, it is necessary to calibrate the VAV box flow grids. Assuming that all flow grids behave similarly and that relative changes in ELA_{25} are more important than the absolute values, then it is necessary to only calibrate one grid and the same calibration can be used for all other grids. The simplest calibration involves a one-point test. The test involves opening one primary air damper after the trunk is sealed; the airflow through the box grid will then be the carrier airflow minus the leakage flow of the trunk. That leakage flow is estimated using the trunk ELA_{25} and duct wall pressure difference. Note that pressure-dependent VAV boxes do not have flow grids installed; a probe to determine box airflow will need to be inserted in each branch being sealed.

The following describes the protocol for sealing up to four downstream sections at a time. This protocol is repeated on other downstream sections as needed.

1. Cover all of the grilles on the downstream sections being sealed.
2. Open the primary air damper of one VAV box; calibrate the airflow through the associated box flow grid.
3. Open the other primary air dampers for the downstream sections being sealed.
4. Determine the ELA_{25} of each branch duct being sealed.
5. If a branch duct is very leaky, inspect the duct for large leaks and manually seal any that are found. Determine the ELA_{25} again if any sealing was carried out.
6. For each branch duct being sealed, if further sealing is needed, install the aerosol sealant injector downstream of the VAV box. Otherwise, skip forward to Step 9 of the downstream sealing process.
7. Turn on the injectors. As sealing proceeds, monitor the duct wall pressure difference and the branch duct airflow changes, and continuously determine the ELA_{25} for each branch duct being sealed.
8. For each branch duct, when its ELA_{25} stabilizes, terminate the sealing, uninstall the injector, close the primary air damper, and uncover the associated grilles.
9. Move to the next unsealed branch. Repeat the protocol from Step 3 onward. If all branches are sealed, continue to Step 10.
10. Restore the system and turn on the system fan (if it was found on).

Refining MASIS for Field Use

The use of the MASIS injection system in the laboratory and field differs in two ways:

1. Lab tests use short compressed air hoses connected to nearby fixed, high-capacity air supplies; field use requires a portable compressed air supply and longer air hoses.

2. In a lab, it is easy to clean clogged injector nozzles with solvents and the time to do so is less critical; field cleaning of nozzles is more difficult because of limited facilities to accommodate solvents and the time available for cleaning is often limited.

The following describes our refinements to MASIS for field use.

Compressed Air Supply: For field use, each injection station requires a portable air compressor. The compressed air pressure for liquid sealant atomization is 50 psi and the airflow is 3 to 5 cfm. The compressor needs to operate on the 110 V electrical supplies commonly available in buildings and is limited to single-stage devices for portability. Compressors that meet these requirements are commercially available, but our flow and pressure requirements are near their capacity limits.

The compressor could be mounted on the injection cart to improve system portability. However, compressors are noisy, so locating the compressor 50 to 100 feet away from the work area is preferable. This means that compressed air hoses of this length with a low pressure drop are needed. To determine an appropriate hose size for the compressed air lines, we calculated the pressure drops for the flow range that we use, based on a roughness factor 0.0004 feet. For 3/8" I.D. air hose, the pressure drops range from 5 to 13 psi per 100 feet of hose. For 1/2" I.D. air hose, the pressure drops are much lower: 1 to 2 psi per 100 feet of hose. To take advantage of the smaller pressure drops, we selected 1/2" I.D. hose and limited the length to 50 feet for portability reasons.

Nozzle Clogging: The heated compressed air that dries the sealant after it leaves the injector nozzle has an undesirable side effect: it also heats up the whole nozzle assembly. The increased nozzle temperature causes sealant to gradually deposit on the wall of the liquid insert inside the nozzle. When enough sealant accumulates in the insert, it becomes clogged and the sealant flow stops.

Lab tests under our DOE research program addressed the clogging issue. One technique that we identified and applied under that program was to use compressed air to flush the nozzle after an injection sequence is complete. A bypass valve was installed between the liquid and compressed air lines. To flush the nozzle, it is necessary to turn off the sealant pump and heater and open the bypass valve simultaneously. To avoid rupturing the sealant lines and to prevent backflow through the pump from the compressed air introduced into the sealant lines, we upgraded the peristaltic pump and lines. The new pump can provide 63 ml/min of sealant flow at 100 psi. The pump has a metering capability and can be set to any desired flow, within a 10:1 turndown ratio. Our lab tests indicate that the pump and flushing system are effective in providing the desired range of sealant flows (20 to 50 ml/min) for double the number of injection sequences before clogging (10 sequences instead of 5). Further work funded by DOE is underway to develop a nozzle that is less susceptible to clogging.

Testing the Sealing Process Monitoring System

MASIS uses an auto-zeroing eight-channel pressure transducer (Automated Performance Testing system, APT) to measure the duct wall pressure differences, as well as the flow meter pressure differences used to determine leakage airflows. Using custom software that we developed to monitor up to four simultaneous sealing processes, a laptop computer connected to the APT displays the duct wall pressure differences and carrier airflows, calculates the effective leakage areas (ELA_{25}), and determines the sealing rates versus elapsed time. Both the upstream and downstream sealing stages use the same centralized monitoring system. Although sealing each of the VAV branches in the second stage is independent and separate monitoring stations could be used, it is advantageous for capital cost and efficiency reasons to use the same centralized monitoring system in both stages. We have extensively tested the software and monitoring system in our laboratory and determined that this system is fully functional. Figure III-7 shows sample results from a single-branch duct-sealing test in our laboratory.

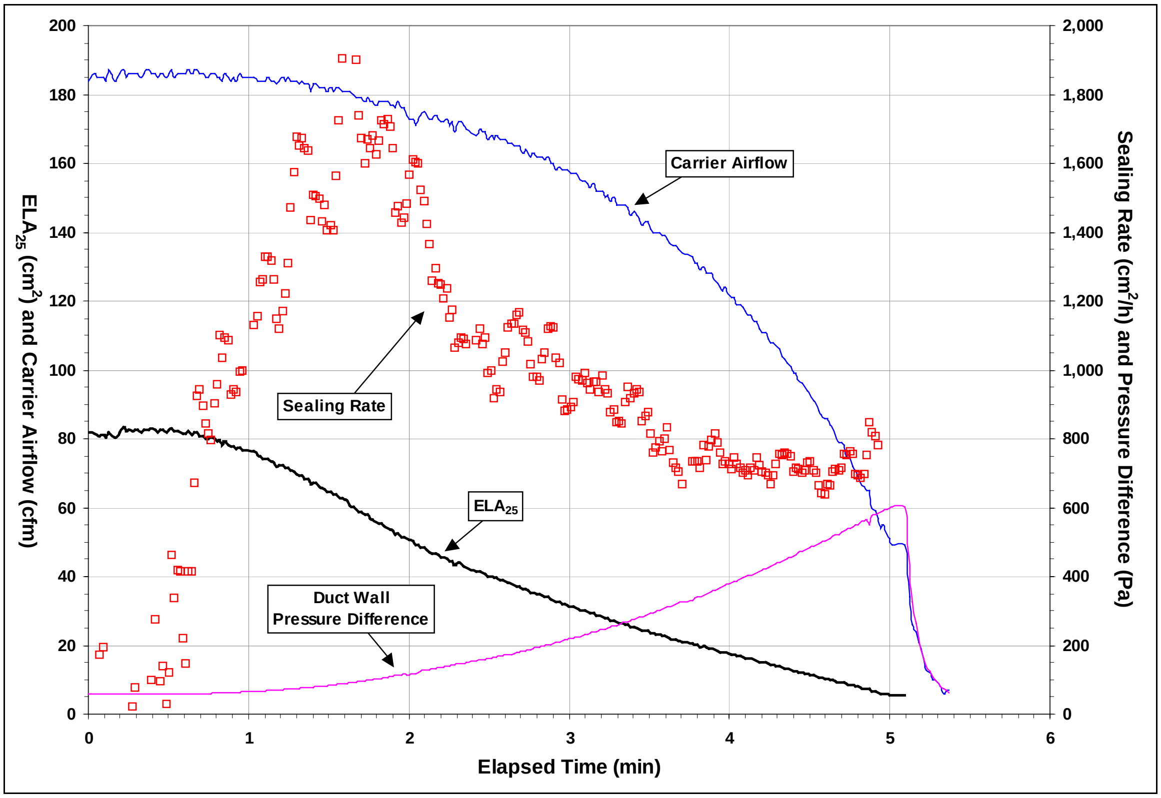

Figure III-7. Sample results from a single-branch duct-sealing laboratory test. The injector was turned off after running about 5 minutes; the carrier airflow fan was turned off about 5 seconds later. The effective leakage area (ELA_{25}) of the duct section was reduced about 94% over the 5-minute period.

Other Duct Sealing Issues

We considered other duct sealing issues in this project, but after further laboratory and field investigations, discounted them in terms of field retrofits. One example involves VAV box air leakage. Our laboratory tests of one VAV box with an induction fan indicated that about 30% of the box leakage is across the partition separating the primary air path from the induction fan inlet, and about 70% of that is associated with induction fan backdraft damper leakage. Our field tests indicated damper leakage could be even larger (2 to 3 times greater), but it seems that damper leakage may not be a significant issue when compared with other duct leakage. In any event, field retrofits to reduce backdraft damper leakage would be difficult because of limited access and aerosol sealing cannot be used to seal the damper edges (the damper needs to open when the induction fan operates). Providing better sealing for the backdraft damper and partition appears to be a design and manufacturing issue more so than an installation or field retrofit issue.

Another example involves air leakage at supply grille edges. Our component leakage tests in the test building indicated that a substantial fraction of the leakage area in downstream duct sections is located at the supply grille edges. However, our leakage flow tests with and without grille edge seals indicated that this leakage area is of little concern, likely because operating pressures at these leaks are very low.

Next Steps

Given the definition of aerosol sealing protocols here and the positive results from our lab tests, we are ready to deploy the multiple injector aerosol-based sealing technology to seal duct leaks in large commercial buildings. The next step is to demonstrate its performance in a sample of large commercial buildings.

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