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Enclosures and the use of exhaust systems are widely applied strategies for containment during building restoration. The concept involves the use of temporary structures, usually constructed from sheet polyethylene (sheet poly), and one or more negative air movers located inside. The negative air movers' discharge filtered or otherwise purified air into the atmosphere. Removal of air from the interior of the temporary structure creates a pressure differential as compared to the exterior; that is, atmospheric pressure inside the enclosure is less than that outside. This difference in pressure induces movement of air into the enclosure (from higher to lower pressure).

The flow of air into the work zone prevents migration of airborne contamination outward from the enclosed structure to the exterior. The exterior can be the external surroundings or other parts of an occupied building.

Exhausting the work zone is one approach to establishing differential pressure between the occupied zone and the work zone. Another approach is to pressurize the occupied zone relative to the work zone, forcing air to escape through known and unknown paths into the work zone. This strategy is suited to situations where establishing a seal between the occupied zone and work zone or the work zone and external surroundings is difficult to achieve, and where unfiltered emissions to the external surroundings do not pose a health risk.

Pressure-Flow Relationships

Despite their seeming emptiness, air and other mixtures of gases and pure gases behave as fluids, which have easily measurable physical properties, will flow and will exert pressure on the walls of their containment. These characteristics are most readily apparent when considering the most prevalent fluid in our lives: water. Under pressure, water flows through other fluids like a jet and flows along surfaces and through channels. Water also flows in and fills enclosed structures, such as piping and where there is no air, as in home water supply piping.

A motive device pushes or pulls fluids through piping or ducting. Fluids exert pressure in the direction of flow (velocity pressure). Velocity pressure is always a positive value relative to atmospheric

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GATIVE) PRESSURE

Macro containment showing the sag in the ceiling due to negative static pressure.

pressure. Similarly, fluids exert pressure against the walls of the structure that contains them (static pressure). Static pressure is positive (outward) relative to atmospheric pressure downstream from the motive device and negative (inward), upstream. When flow is completely blocked, velocity pressure is zero and the total energy of the motive source transfers seamlessly to static pressure. When static pressure is minimized, the energy of the motive source transfers seamlessly to velocity pressure minus losses due to friction.

Velocity pressure and static pressure are measures of the energy transferred to the fluid by the motive source. Understanding the relationship between pressure and energy is critical to understanding the dynamics that occur in containments. Positive static pressure attempts to force apart the surfaces of the containment. Negative static pressure attempts to collapse the containment.

Fans are important devices for building restoration. A fan can impart energy to the air solely as velocity, as in the jet created by a carpet drying fan in an unsealed enclosure. Energy added to the air in a sealed enclosure with no inward leakage by a ventilation system that discharges to the outside is expressed only as negative static pressure exerted against the walls of the containment. Usually the energy of the fan partitions between flow and negative static pressure.

The seamless interconversion of energy between negative pressure and flow in an uncontrolled versus deliberately controlled manner raises technically and economically important questions. IICRC S520 requires maintenance of the enclosed area under -5 to -7 Pa (-0.020 to -0.028 in wg) relative to atmospheric pressure, when monitored. (The unit Pa refers to Pascals and in wg refers to inches of water gauge, both units of pressure used with manometers.) The IICRC S520 requires exchanges of at least four volumes of air in the structure per hour.

The history and justification behind the choice of these values is not clear. Appendix J of EPA 560/5-85-024 (Guidance for Controlling Asbestos-Containing Materials in Buildings, June 1985), on negative pressure systems for asbestos abatement recommends four air changes per hour in the enclosure based on "engineering judgment." The document further comments about the use of "smoke" tubes and visual observation of air flow and inward movement of weighted poly flaps on access doorways leading into enclosures. The document describes quantitative measurement of pressure difference between the interior and exterior of the enclosure using a magnehelic gauge, but provides no guidance on the appropriate numerical value.

The value of -5 Pa (-0.02 in wg) does appear in private training courses on asbestos abatement delivered in the late ‘80s with the comment that the curtains installed in the containment “billow inward” at this level of pressure differential. There is little in print in recognized textbooks on ventilation regarding negative pressure and its effects. Industrial Ventilation (25th Edition) published by the American Conference of Governmental Industrial Hygienists, indicates that negative pressure of -0.02 in wg acting on a crack would produce a velocity of 340 ft./min. at room temperature. Corresponding values for -0.025 in wg and -0.030 in wg are 380 ft./min. and 415 ft./min., respectively. These are large air velocities compared to levels recommended to control emissions at the face of a spray booth.

The IICRC S520 appears to have the most real-worldly application of the sources mentioned in this discussion, requiring a note of caution that attaining these levels of negative pressure can lead to collapse of the containment.

Static pressure and volumetric flow requirements, as stated in the IICRC S500 and antecedent documents are not independent quantities. They are related to each other through the common denominator of energy. One can be achieved at the expense of the other through the expenditure of a given amount of energy. The question is whether the values mentioned should be carved in stone as requirements or considered as guidelines. The issue to emphasize is that the ventilation installed in the enclosure must prevent outward migration of contamination. Achieving this end-point can occur in different ways through the creative application of ventilation.

Achieving and maintaining these levels of negative pressure and volumetric flow now can be viewed in terms of the size, type and number of air movers required in a particular situation. Centrifugal fans provide the greatest ability to meet these requirements, and this is the reason this type of air mover is found in negative air units. Centrifugal fans can generate high levels of static pressure, which is transferable to volumetric flow.

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Figure 1. Air movers configured to pressurize the interior of the occupied structure. The location is an enclosed porch into which heated air was discharged to supplement heat provided by electric baseboard heaters.

An important starting-point in the pressure-flow discussion is the material of construction of the containment. The containment can incorporate the walls of structure constructed from masonry or gypsum board (drywall), and temporary walls constructed from sheet polyethylene (sheet poly).

Masonry and gypsum board are essentially rigid and not affected visibly by the negative static pressure. Temporary walls constructed from sheet poly, however, display a different response. The inward bowing of sheet poly in a temporary structure induced by negative pressure leaves a lasting impression on anyone who has observed it. In an environment containing nonyielding boundary surfaces, maintaining the pressure-flow relationship should not pose undue difficulties; however, in an environment containing flexible boundary surfaces, this could pose major technical challenges. Following are descriptions of two very different projects requiring containments that were handled by Genesis Restorations Ltd.

Example 1: Noncompliant Surfaces

The first situation concerned the crawlspace located under a large home which now serves as a daycare center for young children. The original building is about 50 years old. The crawlspace covers the entire floor area of the structure and measures about 10 m by 15 m (33 ft. by 50 ft.). It is about 1 m (3 ft.) high to the floor joists, and contains a concrete floor and walls, solid wood floor joists and a wooden subfloor. In some areas, the space contains vertical supports for the floor, piping and ductwork.

Access is available from a hatch measuring about 1 m (3 ft) square in the floor of an isolated utility room located at the rear of the building. This room is accessible only from an outside door and has no contact with the interior of the building. A second hatch measuring about 0.6 m (2 ft) square located outside the building in the same area provides additional access. A concrete wall running down the center of the building divides the crawlspace into two halves. A small opening in the concrete wall provides access to the second half of the crawlspace.

The crawlspace contained fibrous glass insulation that had fallen from the floor joists, as well as paper, wood and other debris, mud, sludge and rodent droppings and carcasses. The crawlspace had experienced several wetting episodes involving plumbing leaks and seepage from outdoor sources over the years. The presence of condensed or standing water in the space for a prolonged period and the presence of food sources, such as cellulose in paper and building materials, coupled with hot summer weather, are highly conducive to microbiological activity. Required remedial actions are likely to aerosolize large numbers

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of spores. This situation can produce adverse consequences on workers in the space and occupants of the daycare center.

The nature of the situation required the daycare center to operate continuously during this work. The structure contains many penetrations between the occupied area and the crawlspace. The crawlspace also contains many openings leading to the exterior surroundings. Establishing an effective seal at these interfaces would have been very difficult and time-consuming. An additional complicating factor was the cold weather. Cold air and cold surfaces in the crawlspace coupled with unheated supply air could rapidly have caused cold stress and possibly frostbite.

The strategy employed here was to pressurize the daycare center relative to the crawlspace using HEPA-filtered outdoor air and to allow air to vent from the crawlspace through existing openings and the open hatches to the external surroundings. To pressurize the interior of the structure, two negative air movers (total rated supply of 3,000 cubic feet) discharged continuously into the daycare center (Figure 1). Electrical baseboard heaters provided heated air to the interior of the daycare center. This configuration eliminated concerns about behavior of furnace flues. A differential manometer established the reliability and consistency of pressurization at several locations in the building. Differential pressurization of the daycare center relative to the crawlspace was consistently in the range of 0.01 to 0.02 in wg.

Figure 2. External propane furnace and propane bottles. Note the discharge stack for combustion gases.

Figure 3. Heated air provided to the crawlspace.

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The lower pressurization occurred when the front door of the building was opened for a prolonged period.

Provision of a large volumetric flow of outdoor air into the building strained the capacity of the electric heating system. An external propane furnace solved this issue, as well as the presence of cold air and cold surfaces in the crawlspace (Figures 2 and 3). This furnace contains a heat exchanger to prevent entry of

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Figure 4. The network of ropes that held up the sheet poly to create the ceiling of the containment.

Figure 5. The exterior doors that provided access to the gymnasium.

combustion gases. Heated air was provided periodically to the enclosed area from which the negative air movers drew supply air, as well as to the crawlspace. This system proved to be highly effective.

The situation highlighted the fact that supply and exhaust rates require careful consideration. Pressurization of the occupied level considerably simplified the necessity to create and maintain differential (negative) pressure in the crawlspace. From the perspective of maintaining a pressure differential of -0.020 in wg, the walls of the structure were noncompliant (rigid) relative to the pressures involved during this work.

Example 2: Compliant Surfaces

The second situation involved removal of a gymnasium floor in a high school following some water damage. The gymnasium was built above a crawlspace measuring about 1 m high that served as a plenum chamber for distribution of heated air to the gym. The school was to remain operational during this work.

Gymnasiums occupy large surface areas. The airspace above the floor is considerably larger than that needed for the work area. The airspace requires ventilation if included in the containment, since its surfaces could become contaminated during the ensuing activity, so there is considerable incentive to reduce the ceiling height as much as possible. This avoids the need for decontamination at the conclusion of the work activity.

Genesis Restorations decided to use a novel system to create the ceiling of the enclosure: a grid of ropes (Figure 4). The gymnasium was completely enclosed in sheet poly, and this included an access hallway located along an existing hallway that ended at exterior doors (Figure 5).

During set-up, Genesis had experienced difficulty achieving differential pressure of -0.020 in wg and required flow. The system of ropes and the large surface of plastic on the walls and ceiling were highly compliant, meaning that they displayed considerable give and recovery. The more compliant the surfaces act, the more energy needed to establish and maintain the differential pressure reading of -0.020 inches of water gauge.

A series of measurements were obtained using an air velocity meter (Alnor Model 6575) and a differential pressure meter (Omniguard 4 Differential Pressure Recorder). All known openings into the space were sealed, leaving only the opening surrounding the probe of the air velocity meter (about 3.25 square inches), which was fixed in this position for the duration of sampling. Openings of progressively larger areas were cut into the flap at the access/egress hallway. The outside door to the building remained closed, except for the last sample. The differential pressure meter was located in the ceiling of the enclosure at the center of the gym. Measurement of ceiling height occurred at this location.

School was not in session the day of these measurements. The winds were calm and the sky was overcast. Measurements (Table 1) occurred over a continuous period without interruption.

The key to understanding this data is contained in the last measurement. In this case, the flap contained a large opening and the outer door to the building was opened simultaneously. The pressure differential between air inside the structure and air outside was extremely small. The portable ventilation system induced flow of 7098 ft^3/min. into the enclosure under essentially unrestricted conditions.

When the door to the building was closed under the same condition, the pressure differential increased only 0.01 in wg. yet the volumetric flow decreased by a factor of four. This indicates that a seemingly small increase in static pressure exerted against the containment produces a dramatic decrease in flow. The gap in the door frame through which air was forced to flow imposed the controlling resistance to flow. Similarly, the opening in the flap under the same conditions appears to have imposed minimal resistance to flow.

This would suggest that larger openings in the flap, such as those that would occur when a person or bag of material passed through the opening would produce a large inflow of air, provided that the door to the exterior of the building was open, or conversely, little

Table 1.

Airflow & Differential Pressure Characteristics

Opening Size in	Opening Area ft^2	Velocity ft / min	Volumetric Flow ft^3 / min	Differential Pressure in wg	Ceiling Height in
probe opening	0.023	1690	38	-0.030	62.5
1 x 1	0.03	1670	49	-0.0295	62.5
2 x 2	0.05	1620	82	-0.029	62.75
3 x 3	0.085	1575	134	-0.029	62.75
4 x 4	0.13	1555	208	-0.028	62.75
5 x 5	0.2	1490	292	-0.028	62.75
6 x 6	0.27	1445	394	-0.027	63
7 x 7	0.36	1335	484	-0.026	63.25
8 x 8	0.47	1290	602	-0.025	63.5
9 x 9	0.59	1180	690	-0.024	63.5
10 x 10	0.72	1100	789	-0.024	64
11 x 11	0.86	1005	867	-0.0235	64
12 x 12	1	930	951	-0.022	64.25
13 x 13	1.2	860	1029	-0.021	64.5
14 x 14	1.4	800	1107	-0.021	64.5
15 x 15	1.6	580	919	-0.020	64.5
16 x 16	1.8	510	918	-0.020	64.75
17 x 17	2	470	954	-0.019	64.75
18 x 18	2.3	440	1000	-0.019	65
19 x 19	2.5	400	1012	-0.019	65.5
20 x 20	2.8	355	994	-0.019	65.5
21 x 21	3.1	420	1296	0.0185	65.25
22 x 22	3.4	405	1370	-0.018	65
23 x 23	3.7	390	1442	-0.0185	64.75
24 x 24	4	340	1368	-0.018	65
25 x 25	4.4	370	1614	-0.018	65.25
26 x 26	4.7	330	1557	-0.017	65.25
27 x 27	5.1	300	1526	-0.017	65
28x 28	5.5	270	1476	-0.018	65.5
29 x 29	5.9	180	1055	-0.0175	65.25
30 x 30	6.3	225	1411	-0.0175	65.75
31 x 31	6.7	260	1741	-0.0175	65
*31 x 31	6.7	1060	7098	-0.007	70

** The outer door to the building was open during this measurement.*

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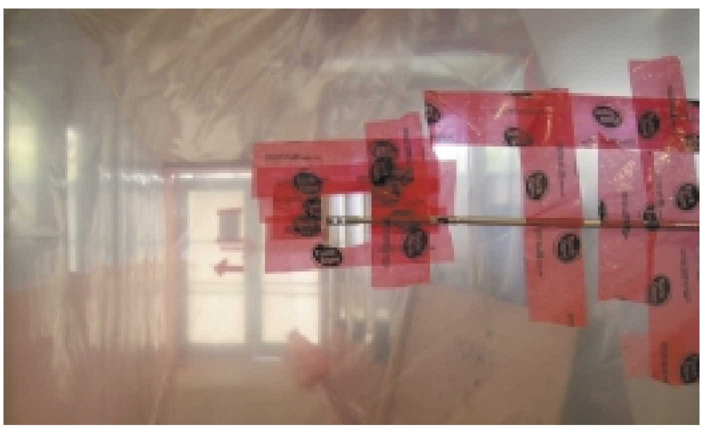

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Position of the probe of the anemometer in the wall of the flap.

The flap containing the probe of the anemometer prior to cutting the first opening.

increase in volumetric flow when the door to the building was closed. In the latter case, the volumetric flow of 1741 ft^3/min. would be spread over a larger surface area and the velocity of flow through the opening would decrease correspondingly from 260 ft./min. The only way to increase inflow through the flapped door leading to the gym would have been to introduce a second source of air to the hallway leading to the enclosure. This result also argues for a direct and unrestricted path of airflow between the work zone in the enclosure and the exterior of the building in order to produce the greatest benefit from the installed ventilation system.

This work involved abrasive blasting using dry ice pellets. Dry ice is frozen carbon dioxide. The abrasive blasting operation involved the supply of compressed air into the enclosure from a mobile compressor. This expansion is around 5.8-fold for a compressor operating at 85 lbs/in^2. That is, 1 ft^3 delivered at 85 lbs/in^2 expands to 5.8 ft^3 at atmospheric pressure. Delivery rate at the compressor was 380 ft^3/min. at 85 lbs/in^2. Actual delivery at the discharge of the blasting gun would be considerably less than this amount due to losses in the small diameter line.

Assuming that the delivery rate was as quoted, the volumetric flow introduced into the enclosure would be 2200 ft^3/min. There is reasonable expectation based on results already discussed that the introduction of air into the enclosure would have a small impact on the pressure differential and performance of the ventilation system, while doors to the outside of the building remained closed. (This work was performed during winter months.)

The data for openings in the flap up to 14 in. by 14 in. (1.4 square feet) indicate a steady increase in volumetric flow as the openings enlarge. At this point the volumetric flow plateaus. This situation suggests that gaps around the outer doors to the building at the end of the access hall have assumed control of the pressure-flow relationship and that the opening in the flap no longer had an influence. This is consistent with the geometry of the situation. Since the work was performed during the winter months, the doors to the exterior of the building remained closed as much as possible to keep in the heat.

Pressure-flow changes occurred as quickly as the physical change in the opening in the flap. Compensation in the pressure differential and ceiling height occurred in the time required (1 to 2 s) to walk to the centre of the gym from the flap in the access door. Compensation (a disturbance moving through the fluid) potentially occurs at the speed of sound in air.

Both of these projects demonstrate how the proper use of containment can affect a restoration project. They also illustrated the principles of air flow and the issues to be considered when constructing a containment.

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