AN EVALUATION OF SHELTER-IN-PLACE STRATEGIES IN FOUR INDUSTRIAL BUILDINGS

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ABSTRACT
Shelter-in-place (SIP) strategies were evaluated in four industrial buildings with volumes ranging from 111 to 3,084 m^3. Air exchange rates were determined to be between 0.61 and 2.81 hr^{-1} using tracer gas techniques, and air tightness was found to be between 12.1 and 41.4 air changes per hour at 50 Pa (ACH_{50}) using fan pressurization methods. SIP strategies were evaluated by measuring concentration reductions of indoor ambient particles relative to outdoors for particles from 0.5 - 5 μm in diameter. The tested SIP strategies included sealing air leakage pathways and deploying portable high-efficiency particle arresting (HEPA) filters. Sealing leaks in two buildings increased air tightness but did not reduce indoor particle concentrations. HEPA filters reduced indoor particle concentrations in all buildings. The effectiveness of HEPA filtration as a SIP measure against particles depends upon contaminant size, filtration duration, and filter flow rate relative to the infiltration flow rate of the building.

INDEX TERMS
Extraordinary events, HEPA filter, Bioterrorism, Infiltration, Shelter-in-place (SIP)

INTRODUCTION
Information promulgated by the federal government, private foundations, and national laboratories often suggest a shelter-in-place (SIP) protocol for building occupants in the case of an outdoor release of a hazardous pollutant. In cases where evacuation is not feasible, SIP techniques seek to prevent outdoor pollutants from reaching building occupants by intercepting particles either at the building envelope or within the structure by means of filtration or respiratory masks. Mannan and Kilpatrick (2000) cite several examples in which SIP has successfully reduced or prevented occupant injury during hazardous outdoor releases. Additional studies identify general guidelines for deciding if and how to implement SIP in a given situation (Sorensen *et al.* 2004, Mannan and Kilpatrick 2000). Specific assessments of SIP include Ward *et al.* (2005), who model the use of filtration as an SIP technique in residential buildings and found that portable HEPA air cleaners are more effective in houses with lower air exchange rates. A recent study modeling SIP in residential buildings indicates that the building envelope reduces the infiltration of chlorine gas by 50% four hours after release (Chan *et al.* 2004). For particles, experimental studies indicate that the penetration factor across a building envelope is less than one, indicating that, for certain particle sizes, not all outdoor particles enter indoor spaces (Long *et al.* 2001, Liu and Nazaroff 2003). These results indicate that the building itself provides a limited amount of protection from outdoor particulate contaminants. We know of no study, however, that analyzes SIP in industrial buildings despite the fact that these buildings are likely sites of accidental releases and are potential terrorist targets. There has been limited work that characterizes the air leakage of industrial buildings. Perera *et al.* (1991) measured an industrial building's air leakage and found it to be dependent on temperature, wind speed, and the presence of loading doors. In the present study, specific SIP techniques in four industrial buildings are assessed in terms of their effectiveness at reducing indoor particle concentrations relative to outdoor concentrations. An additional goal of this study is to further characterize building tightness and air exchange in industrial buildings.

RESEARCH METHODS
Field testing was conducted in four industrial buildings in Austin, Texas, USA. Site measurements determined building volume as well as floor, window, and door areas. A visual assessment of the buildings identified likely air leakage pathways. Air exchange rates were found using a tracer gas decay test, which depends on factors such as wind speed, inside-outside temperature difference, and the distribution and size of building leaks. This test was performed by releasing a known amount of sulfur hexafluoride (SF_6), an inert and non-naturally-occurring gas, into the structure and measuring its concentration using a Lagus Autotrac Tracer Gas Monitor at periodic intervals.

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Using a well-mixed mass-balance model, the decay in concentration over time determines the rate at which the indoor air is replaced with outdoor air. Leakiness of the buildings was measured using an Energy Conservatory Minneapolis Blower Door at multiple inside-outside pressure differences. Blower door pressurization is largely independent of ambient conditions and thus is useful for comparing building air tightness. Two of the buildings, Sites 1 and 4, had no obvious or easily sealed leakage pathways and thus were not sealed during testing. The SIP strategy of using plastic sheets and duct tape to seal suspected air leakage pathways was used in the other two buildings, Sites 2 and 3, which had large vents to the outside. Blower door and tracer gas measurements were repeated in these buildings after sealing leaks. A second SIP strategy of deploying of 1 to 4 HEPA filters was performed in all four buildings. Indoor and outdoor particle concentrations were measured using a TSI model APS 3321 aerodynamic particle sizer for particle diameters ranging from 0.5 to 20 µm. Simultaneous measurements were not possible, so outdoor measurements were made between indoor measurements. An average of outdoor measurements before and after each indoor measurement was used to estimate outdoor concentrations during the indoor period.

RESULTS

The first tested building, Site 1, was a warehouse-type structure constructed with steel framing with a sheet metal roof and walls. There was no HVAC system or other form of mechanical ventilation. The other three buildings, Sites 2, 3, and 4, had brick walls with concrete floors and ceilings. Only Site 4 had a heating and cooling system, and all four buildings had operable windows. Table 1 summarizes the building characteristics.

***Table 1.** Building Characteristics*

	Building Use	**Area, m^2 (ft^2)**	**Volume, m^3 (ft^3)**	**Notes**
Site 1	Storage warehouse	564 (6,070)	3,080 (109,000)	Loading door area of 62.4 m^2 (672 ft^2)
Site 2	Pump house	84.5 (909)	1,420 (50,100)	Multiple openings in floor to exterior
Site 3	Equipment storage	45.5 (490)	111 (3,920)	3 large ceiling vents to exterior
Site 4	Equipment storage	35.1 (378)	161 (5,690)	Wall-unit packaged HVAC system

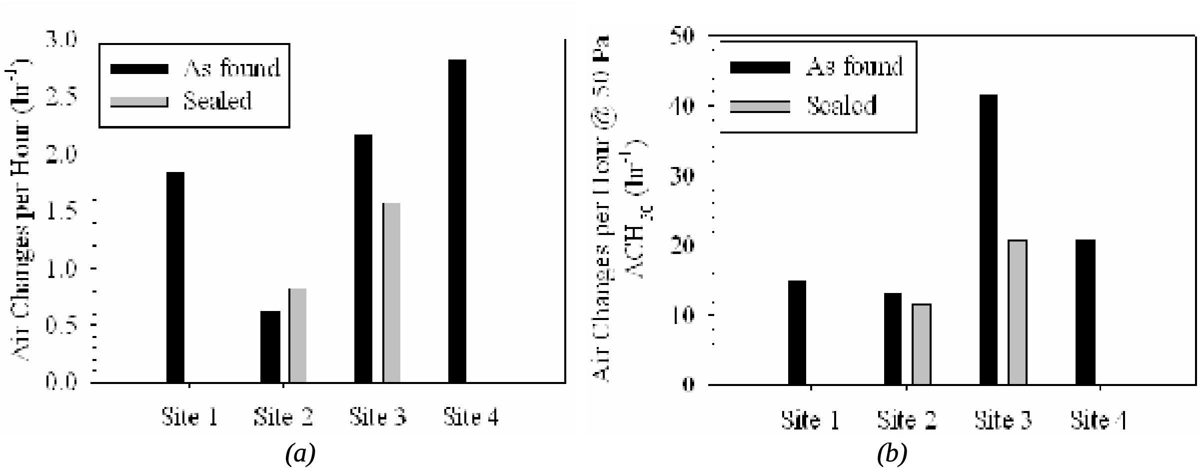


***Figure 1.** Air Exchange from (a) tracer gas testing and from (b) blower door testing*

Figure 1 shows the air leakage and the air exchange for each site. Sites 1 and 4 remained unsealed during testing, while Sites 2 and 3 were evaluated before and after the sealing of known air leakage pathways. Air exchange rates ranged from 0.61 hr^{-1} to 2.81 hr^{-1}. To put these results in context, typical commercial buildings have air exchange rates of 0.5 to 1.1 air changes per hour (ACH), while residential building rates are typically lower at 0.3 to 0.7 ACH (Murray and Burmaster 1995). Site 2 had an air exchange rate that was similar to most commercial buildings, and Sites 1, 3, and 4 had higher air exchange. The tracer gas test at Site 2 showed a slight increase in air exchange rate after sealing leaks, while blower door testing indicated a slight reduction. The small air exchange rate increase may be attributed to varying wind conditions and uncertainty associated with tracer gas measurement and analysis, in addition to the fact that the sealed leaks were likely not major leakage paths. Sealing of the large ceiling vents in Site 3 resulted in a reduction of air exchange. Though the air exchange rate of Site 1 is similar to those of the other sites, a much greater volume of air is exchanged at Site 1 because of the large building volume. Also because of the large volume of Site 1, tracer gas concentration measurements were taken at four locations at this site. The air exchange rate was calculated from the average of the four concentrations, which varied from each other by up to 40% early in the test. The variation among the different locations indicates that Site 1 violated the well-mixed assumption, even though multiple mixing fans were deployed, thereby creating additional uncertainty in the tracer gas results.

The two blower doors used to pressurize Site 1 were able to achieve only a 10 Pa difference between indoors and outdoors because of the large amount of leakage. The data from the low pressures was then extrapolated up to 50 Pa, thus there is a large degree of uncertainty in the results from blower door testing at this site. Sites 2, 3, and 4 needed only one blower door to achieve the 50 Pa. Sites 2 and 3 showed proportionate results between blower door and tracer gas tests. Site 4, however, had a tracer gas air exchange rate proportionately higher than the blower door leakage, likely due to windy conditions during testing.

Indoor and outdoor particle measurements for three particle sizes for Site 1 and Site 3 are shown in Figure 2. Testing of the building as found was performed first, followed by sealing known leaks and blower door measurements, and concluding with HEPA filtration testing. The four sites used four, one, two, and two HEPA filters, respectively. There are two regions of interest on Figure 2a and three on Figure 2b. The first region on both graphs shows as found measurements, without any SIP measures in place. The gaps in Figure 2 indicate blower door testing, during which no particle measurements were taken. At Site 2 and Site 3, air exchange and particle measurements were repeated with leaks sealed. The sealed region is shown on Figure 2b but is not applicable to Figure 2a. The final region on both figures indicates the deployment of portable HEPA filters and the corresponding particle measurements. Measurements were taken at all four sites, but, for illustrative purposes, only data from Sites 1 and 3 are presented.

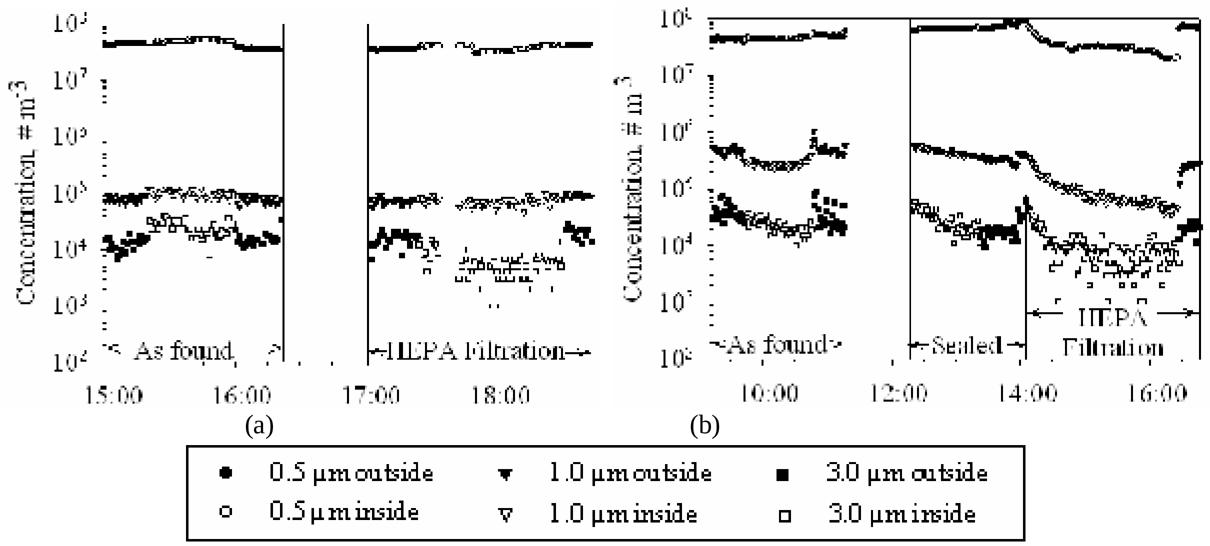
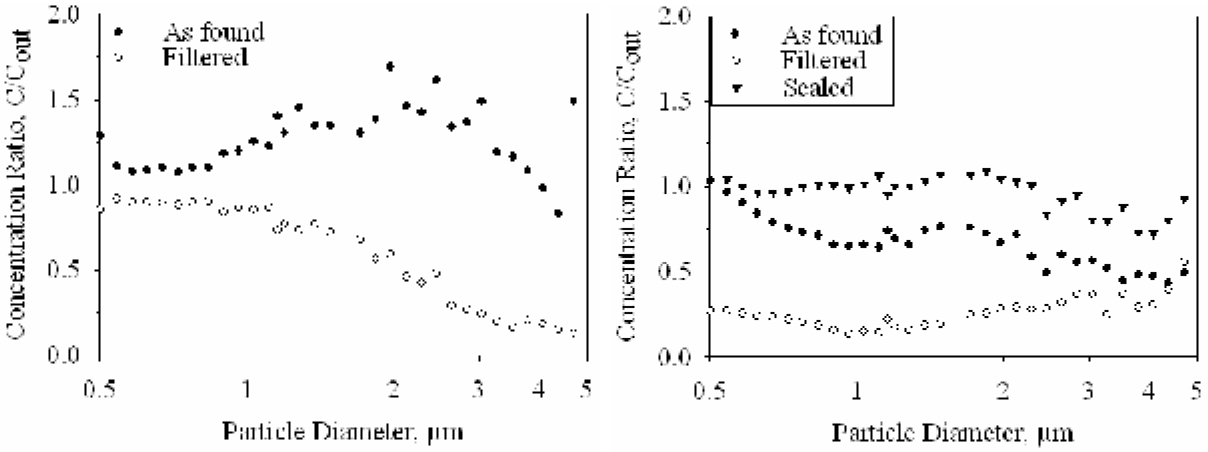


***Figure 2.** Indoor and outdoor particle measurements for 0.5 µm, 1.0 µm, and 3.0 µm particles at (a) Site 1 and (b) Site 3*

Figure 2a indicates that indoor particle levels are not significantly lower than outdoor levels during the as found period at Site 1. The figure further shows that large particle (3 µm) indoor concentrations were higher than outdoor concentrations. This condition may have been a result of particle resuspension indoors that occurred during equipment set-up. The resuspension effect was greater for Site 1 than for other sites because its large volume required more staff and equipment set-up than for other sites. A similar condition was observed at Site 2, which had higher indoor than outdoor concentrations at the time of sealing. HEPA filtration had a noticeable effect in reducing 3 µm particles in Site 1, and a smaller impact for 1 and 0.5 µm particle concentrations.

Figure 2b shows that, initially, indoor larger particle (1 µm and 3 µm) concentrations were lower than outdoor concentrations at Site 3, while small particle (0.5 µm) concentrations were approximately equal to outdoor concentrations. Indoor large particle concentrations were higher than corresponding outdoor concentrations while the building was sealed, likely due to resuspension from set-up activities. The decline of larger particles in Figure 2b during the sealed period can not be definitively linked to sealing, as it may be due a corresponding decrease in outdoor particle concentrations. HEPA filtration at Site 3 reduced particle levels relative to outdoor levels for all measured particle sizes. A graph of data from Site 2 generally resembles Figure 2b (Site 3) with a greater indoor sealed particle concentration relative to outdoors and with slightly less reduction from HEPA filtration, likely due the larger volumetric flow rate associated with infiltration at Site 2. A graph of Site 4 is similar to Figure 2a in that larger particles (1 and 3 µm) were found in higher concentrations indoors than outdoors during the as found testing. HEPA filtration at Site 4 reduced indoor concentrations in a manner similar to that of Site 3 (Figure 2b).

The ratio of indoor particle concentration to outdoor particle concentration is shown in Figure 3. The concentration ratio, C/C_{out}, is a measure of the effectiveness of the SIP technique used. A high concentration ratio indicates low SIP effectiveness. There were not enough ambient particles larger than 5 µm to determine a concentration ratio parameter. Both plots show that HEPA filtration reduced the concentration of indoor particles relative to outdoor particles over the diameter range of 0.5 to 5 µm. For Site 1, filtration reduced the concentration ratio for larger particles (>1 µm) by a factor of 2 to 5. Smaller particles (<1 µm) showed a reduction of approximately 20 %. HEPA filtration at Site 4 had a similar effect as at Site 1, yielding a modest concentration ratio reduction for smaller particles and a greater reduction for larger particles. Figure 3b indicates the inverse to be true for Site 3, at which filtration was more effective for smaller rather than larger particles. Larger particles were reduced by a factor of 1 to 3, while smaller particles were reduced by a factor of 3 to 4. At all sites, filtration reduction took approximately 2 to 3 hours to reach these levels. For the sealed case at Site 3, the concentration ratio was higher than the as found case for the entire range of 0.5 to 5 µm particles. Part of this condition can be attributed to the fact that inside concentrations were higher than outside concentrations when the building was sealed. The higher indoor concentrations indicate that sealing leaks reduced air flow across the building envelope. Thus, indoor concentrations remained similar to their pre-sealing levels.



(a) *(b)*

Figure 3. *Effectiveness of SIP strategies at (a) Site 1 and (b) Site 3*

DISCUSSION AND CONCLUSIONS

Sealing of known leaks reduced the air tightness of both tested buildings. Site 2 had a modest reduction of 7% at 50 Pa, while Site 3, the building with large ceiling vents, showed a reduction of 50% at 50 Pa. Tracer gas testing, which is more indicative of building performance at normal operating conditions, showed an increase in air exchange of 26% at Site 2, likely due to an increase in wind speed during the post-sealing measurements, and a reduction in air exchange of 38% at Site 3. The increase at Site 2 suggests that the SIP technique of sealing suspected leakage pathways was not effective in this building, at least in part because of changing environmental conditions. The results from Site 3, however, show that even if major leakage pathways are correctly identified, sealing the leaks is not necessarily an effective SIP technique. The effect of sealing on particle levels was that the concentration ratio remained closer to pre-sealing conditions and never declined below outdoor levels. Since this ratio was greater than one when the leaks were sealed in both buildings, it showed a tendency to remain so after sealed. For maximum SIP effectiveness, leaks should be sealed immediately after the outdoor release. If sealing is performed after outdoor pollutants have infiltrated into the building, it may hinder pollutant dilution and may cause prolonged exposure to building occupants. This conclusion reinforces the Chan *et al.* (2004) model which found that contaminants slowly exfiltrate from indoors after outdoor contaminants have cleared. A repetition of this study in which outdoor particle levels are significantly higher than indoor levels at the time of sealing would better indicate the effectiveness of sealing as an SIP technique.

HEPA filtration was effective at reducing indoor to outdoor particle concentration ratios over the 0.5 to 5 µm particle range. HEPA filtration reduced indoor particle levels more significantly in smaller buildings with a high filter flow rate to building infiltration rate ratio, i.e. Sites 3 and 4. The four buildings showed approximately an order of magnitude reduction of indoor particle concentrations within 2 hours of filter deployment. These results indicate that, if given sufficient time, HEPA filters with a high clean air flow rate relative to the building infiltration flow rate may provide protection to building occupants from outdoor pollutants for particles that are harmful at very high concentrations. Since the HEPA filters did not eliminate all ambient particles, it cannot be assumed that filtration is an effective SIP technique for particles that are a concern at very low concentrations or for brief exposure times. HEPA filtration, while not completely removing a contaminant, may allow for enough of a reduction in peak exposure to prevent occupant injury. Studies indicate that exposure to a lower concentration of certain contaminants for a long period of time may be safer than brief exposure to the contaminant's peak concentration (Chan *et al.* 2004, Mannan and Kilpatrick 2000). Buildings with high air exchange rates and large volumes, however, require high HEPA filter flow rates in order to be effective. Furthermore, HEPA filtration was shown to require several hours before concentrations reached a level approaching steady state. This time, when combined with filter set-up time, may limit the value of HEPA filtration as an SIP technique. HEPA filtration may also provide occupants with a window to enact additional SIP measures, such as donning protective breathing devices, or to evacuate to a safe room. The contaminant's potency, as well as the time required for proper SIP implementation, should be considered in determining the most effective SIP measures for a given building.

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