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Effectiveness of expedient sheltering in place in a residence

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Abstract

The objective of this study was to evaluate the effectiveness of expedient sheltering in place in a residence for protection against airborne hazards, as outlined in the U.S. Department of Homeland Security (DHS) guidance to the public. An improved method was developed to determine the air flow rate for a shelter inside a house. Expedient sheltering measures (plastic sheeting and duct tape) were applied to a room inside a test house by participants who followed the DHS guidance. Measured air flow rates were used to determine protection factors for various scenarios. Protection factors were calculated for the house and shelter under various occupancy times, weather conditions, and outdoor exposure times for hazardous agents. Protection factors ranged from 1.3 to 539, depending on the conditions. Results indicate that proper sealing can make a substantial difference in the effectiveness of the shelter. Sheltering in place can be most beneficial if people enter shelters before the arrival of a cloud of hazardous agent, and people exit shelters as soon as the cloud passes over. However, sheltering in place can be detrimental if people enter or exit shelters too late. CO_2 and O_2 concentrations inside the shelter are not likely to reach dangerous levels under most scenarios, but concentrations could reach dangerous levels under certain conditions, and concentration levels could affect individuals with respiratory problems.

Keywords: Shelter in place; Expedient; Residence; Protection factor

1. Introduction

Sheltering in place is a tactic for reducing human exposure to hazardous chemical, biological, or radiological agents in the event of an accidental or intentional airborne release into the outdoor environment. Exposure may be reduced when people take shelter inside a building rather than being outdoors.

Several studies found in the literature have evaluated the effectiveness of sheltering in place. Anno and Dore [1] evaluated the effectiveness of sheltering as a protective action against nuclear accidents involving gaseous releases. They fitted experimental measurements to an empirical relationship in which the net air exchange rate varied with wind speed and temperature difference. Christy and Chester [2] found that a room sealed with polyethylene sheeting and tape provided a protection factor at least 10 times greater than the house as a whole when challenged with aerosolized spores of *Bacillus globegii*. Birenzvige [3] found that the filtering effect of the building shell increases the protection factor during sheltering. Prugh [4] calculated that, for a typical dwelling and a vapor plume lasting 10 min, the exposure indoors would be about one-tenth of the outside exposure. For other types of dwellings and releases, the indoor exposure could be as little as 1% of the outdoor exposure. Stearman [5] found that filtering of chemical vapors or gases by building materials increases the protection factor. Davies and Purdy [6] calculated indoor and outdoor concentrations during hypothetical toxic gas releases and found that sheltering in place can be beneficial by reducing the exposure. Wilson [7] evaluated variation in indoor shelter effectiveness, and found that variability in

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construction causes houses in Canada and the U.S. to vary in air leakiness by about a factor of two above and below the mean value.

Rogers et al. [8] produced an extensive report, *Evaluating Protective Actions for Chemical Agent Emergencies*, that included an evaluation of sheltering in place. In the report, five types of sheltering are defined. Normal sheltering is defined as taking refuge in existing, unmodified buildings and involves closing all windows and doors and turning off all HVAC equipment. Expedient sheltering is defined as taking refuge in existing structures and involves taking simple, rapid measures at the time of an incident to reduce infiltration, such as applying plastic sheeting and tape, in addition to taking normal sheltering measures. Enhanced sheltering is defined as taking refuge in structures in which infiltration has been reduced before an incident by weatherization techniques such as caulking and weatherstripping. Specialized sheltering is defined as taking refuge in commercial tents or structures explicitly designed for protection in hazardous environments. Pressurized sheltering is defined as taking refuge in existing or specially constructed structures that are pressurized with filtered air. Pressurized sheltering provides maximum protection, but expedient sheltering requires only minimal resources. Rogers et al. evaluated expedient sheltering with tracer-gas experiments on 12 single-family homes. Expedient measures were applied by household members using written instructions and checklists. The time to implement the expedient protection was recorded. Results showed a reduction of average air exchange rates. Variability in the reduction of air exchange rates likely resulted from the way individuals implemented the taping and sealing.

Engelmann [9] evaluated the effectiveness of sheltering from plutonium. Engelmann conducted an extensive survey of previous air exchange measurements and developed an empirical relationship between wind speed, temperature differences, and exchange rate. Blewett et al. [10] evaluated expedient sheltering in place for the Chemical Stockpile Emergency Preparedness Program (CSEPP). Researchers conducted tracer-gas experiments on 10 residential buildings and two mobile homes to determine the effectiveness of expedient measures. Expedient measures were applied by technicians, and expedient measures were shown to substantially reduce air exchange rates. Blewett and Arca [11] subjected a two-room cottage of conventional construction to a series of transient vapor challenges with sarin, mustard gas, and methyl salicylate (a simulant for mustard gas) to measure the protection afforded by sheltering in place. Sorption of agent vapor was found to produce substantially higher protection factors than are predicted simply by air exchange. A consumer-type, carbon-filter, air purifier was found to significantly increase the protection factor.

Yuan [12] used an indoor air pollution model to determine the degree of protection offered by sheltering in place and concluded that small buildings offer a modest degree of protection in the event of an outdoor release of a biological agent, assuming that the attack occurs without notification, and the building inhabitants remain indoors for a substantial period after the attack. Argonne National Laboratory [13] described a concept and a methodology that can be used to make the critical decision on when and how to end sheltering in place. CSEPP [14] assessed the state of the art for sheltering in place, identified steps required to ensure that sheltering in place is used appropriately and effectively, and identified changes to CSEPP guidance and policies. Sorensen and Vogt [15] examined the effectiveness of expedient protection strategies. They concluded that using a wetted towel as a vapor barrier at the bottom of a door should be discouraged, and taping the bottom of the door will provide greater infiltration reduction. Sorensen and Vogt [16] reviewed issues associated with the use of expedient sheltering materials and the effectiveness of this strategy and concluded that duct tape and plastic are appropriate materials for sealing. The National Institute for Chemical Studies (NICS) [17] reviewed scientific studies of sheltering in place and reviewed chemical accidents where sheltering in place was used as a public protective action. NICS concluded that sheltering in place is a good way to protect the public during chemical emergencies.

The U.S. Department of Homeland Security (DHS) [18] produced guidance for the public to prepare for terrorist threats, and the guidance included basic instructions for sheltering in place using normal and expedient measures. Included in the guidance for sheltering in place were instructions to go inside; lock doors; close windows, air vents and fireplace dampers; turn off fans, air-conditioning and forced air heating systems; go into an interior room with few windows, if possible; and seal all windows, doors and air vents with plastic sheeting and duct tape. A diagram showing how to seal a door, window, fan, and vent was also included. The objective of the study described below was to evaluate the effectiveness of expedient sheltering in place, as outlined in the DHS guidance.

2. Methods

2.1. Test facility

A series of experiments was performed in a residential test house located in a suburban neighborhood with large trees and other single- and 1(1/2)-story houses. The test house was a single-story, conventional, wood-frame residence with 131 m^2 of floor area. An interior bathroom with no exterior walls was used as a shelter. Rooms with and without exterior walls were previously tested by Rogers et al. [8] and Blewett and Arca [11]. Generally, rooms with exterior walls can be effective shelters, but internal rooms tend to be more effective.

2.2. Test participants

Men and women of various ages and occupations were recruited as participants in the study. Participants completed questionnaires before participating in experiments. The questionnaire included questions on prior knowledge about sheltering in place, ability to perform tasks, age, and occupation. Plastic sheeting, duct tape, and the DHS guidance for sheltering in place were furnished to the participants. Up to 60 min was allowed for participants to complete the sealing task, and the time required to complete the task was recorded. Participants were questioned on whether they had any difficulty in completing the task. The sealing was visually inspected after each experiment.

2.3. Test procedure

In each experiment, a tracer gas, sulfur hexafluoride (SF_6), was injected into the house before the shelter was sealed. The tracer gas was well mixed inside the house using the heating/air-conditioning (HAC) system fan and box fans until the SF_6 concentration was relatively uniform throughout the house. The concentration was measured inside the bathroom and at five other locations in the rest of the house. Concentrations were measured with a Bruel & Kjaer model 1302 photoacoustic gas analyzer. The instrument was calibrated by the manufacturer on an annual basis, and a zero and span check was performed on each day of the experiments.

In each experiment, the participant sealed the room, including the bathroom door, with a large sheet of plastic, as described in the DHS guidance. When the sealing of the bathroom was completed, a slit was cut in the sheet of plastic covering the door, so the participant could leave the shelter through the opening in the bathroom door. After the participant left the shelter, a technician sealed the slit in the plastic with tape, and sealed the opening in the door with plastic sheeting and tape. The HAC system was turned off. Doors, windows, and the fireplace damper were closed, and ventilation fans were not operated. A small fan was operated inside the sealed-off shelter, and box fans were operated in the rest of the house to mix the tracer gas for accurate measurement. After these tasks were completed, the participant and the technician left the house. Since the tracer-gas concentrations were nearly the same in the bathroom and in the rest of the house before the bathroom was sealed off, the activities of the participant and technician caused little perturbation of the SF_6 concentrations in the shelter and the house. SF_6 concentrations measured over time were used to determine air flow rates between the shelter and the rest of the house and between the rest of the house and the outdoors, as described below. Meteorological conditions including temperature, relative humidity, barometric pressure, wind speed, and wind direction were measured near the house at a height of 9.1 m above ground level.

Nine experiments were conducted in September 2003 when the temperature difference between the inside and outside of the house was small, hence the air exchange rate was low. Nine experiments were repeated in January and February 2004 when the temperature difference between the inside and outside of the house was large, and the air exchange rate was relatively high. Three experiments were performed in April 2004 with a technician remaining inside the shelter while concentration measurements were recorded to verify that slitting the plastic and sealing the opening in previous experiments did not cause substantial additional leakage. Three experiments were also performed in April 2004 with the bathroom door closed but with no sealing in place for comparison with previous results, and two experiments were performed with only the bathroom door sealed.

2.4. Determination of air flow rates

In previous studies in the literature [8,10], a common tracer-gas method [19] has been used to evaluate the effectiveness of sheltering in place. After the tracer gas is well mixed inside the house, the concentration of the gas exponentially decays over time, and the air exchange rate is calculated from measurements of the concentration as follows:

$$A = \frac{-\ln[C(t_1)/C(t_0)]}{t_1 - t_0} \quad (1)$$

where A is the air exchange rate; $C(t_1)$ the tracer-gas concentration at time t_1; $C(t_0)$ the tracer-gas concentration at time t_0; t the time.

Although the tracer-gas method works well to determine the air exchange rate for the whole house, this method cannot be used to determine an inter-zone air flow rate. The tracer-gas method is valid when the outdoor concentration of the tracer gas is negligible and when the air exchange rate is constant. However, the tracer-gas method is not suited for determining the air flow rate for a shelter within a house, because the concentration of the tracer gas outside of the shelter (within the rest of the house) changes over time. Measured concentrations within the shelter do not fit an exponential decay curve, and this is especially apparent when the shelter is first sealed off from the rest of the house, as shown in Fig. 1. The figure shows measured concentrations inside a shelter and inside the rest of the house. These data were obtained following the experimental procedure described above. The SF_6 concentration was nearly the same in the bathroom and in the rest of the house before the bathroom was sealed off. The measured concentrations in the rest of the house fit an

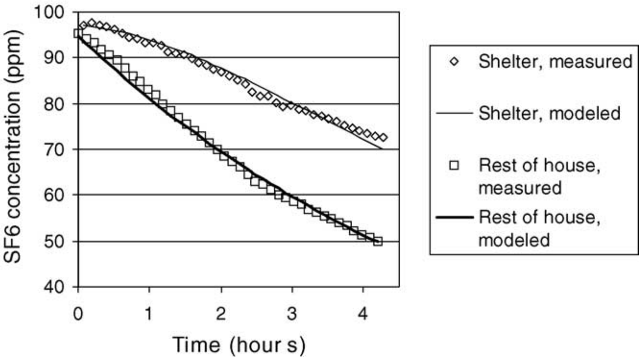

Fig. 1. Tracer-gas concentration vs. time.

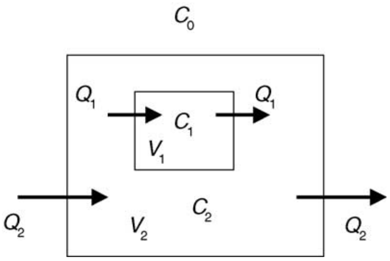

Fig. 2. Diagram of a house with a central room used as a shelter.

exponential decay curve, but the measured concentrations in the shelter did not fit an exponential decay model.

An improved method has been developed to more accurately determine the air flow rate between the rest of the house and the shelter based on tracer-gas concentrations. The improved method is based on an assumption that, for an interior room used as a shelter, most of the air exchange in the shelter is with the rest of the house. This assumption is consistent with our observations and with observations found in the literature. Rogers et al. [8] noted that "... central room exchange measurements are believed to be dominated by exchange between the rest of the house and the central room."

In Fig. 2, a simple, two-dimensional diagram is shown of the floor plan of a house with a central room used as a shelter. Differential equations for the mass balance model corresponding to the diagram are as follows:

$$V_1\frac{dC_1}{dt} = Q_1C_2 - Q_1C_1 \tag{2}$$

$$V_2\frac{dC_2}{dt} = Q_2C_0 + Q_1C_1 - Q_1C_2 - Q_2C_2 \tag{3}$$

where V_1 is the volume inside shelter; V_2 the volume inside rest of house; C_0 the gas concentration outside the house; C_1 the gas concentration inside shelter; C_2 the gas concentration inside rest of house; Q_1 the air flow rate between the shelter and the rest of the house; Q_2 the air flow rate between the rest of the house and the outdoors; t the time.

Eqs. (2) and (3) can be solved either analytically or numerically by specifying the initial conditions: initial time, t_0, and initial concentrations, $C_1(t_0)$ and $C_2(t_0)$.

When tracer-gas experiments were conducted, the outdoor concentration of tracer gas, C_0, was negligible. The concentrations C_1 and C_2 were measured over time in the experiments, and the volumes V_1 and V_2 were also known from measurements. Initial conditions for the concentrations and time were obtained from measurements. The air flow rate parameters Q_1 and Q_2 were numerically calculated from the equations above with mathematical software, MicroMath SCIENTIST, using the method of least squares. For all experiments, the correlations between measured and modeled concentrations had R^2 values of greater than 0.99. The goodness of fit for the model is illustrated in the example in Fig. 1.

For each experiment, the ratio of the air flow rates, Q_2/Q_1, was calculated. This ratio may be compared for experiments conducted under similar weather conditions to indicate variation in the quality of sealing, with higher ratios indicating better quality of sealing.

2.5. *Determination of protection factors*

The same model, based on Eqs. (2) and (3), was used to evaluate exposures under various sheltering in place scenarios using the experimentally determined air flow rates. Cumulative exposure is defined as the inhalation concentration of a hazardous agent integrated over time:

$$E = \int C\,dt \tag{4}$$

The outdoor concentration, C_0, for a hypothetical hazardous agent was specified over time as a Gaussian distribution to approximate the exposure profile for a plume of gas or vapor passing over a home. The concentrations inside the shelter and the rest of the house, C_1 and C_2, were numerically simulated with the model.

The protection factor, PF, is defined as the ratio of the cumulative exposure outdoors over the cumulative exposure inside the house or shelter: $\mathrm{PF} = E_{\mathrm{outdoors}}/E_{\mathrm{inside}}$. The protection factor provides a quantification of the benefit of sheltering in place. Protection factors were determined for various sheltering scenarios using the model described above. Scenarios were simulated for weather conditions with small and large temperature differences between the indoors and outdoors using low, mean, and high measured values for the house and shelter air flow rates. Protection factors were calculated for outdoor exposure times of 0.25, 1, and 2 h, and for house occupancy times of 0.25, 1, 2, and 3 h. For all the simulated scenarios, it was assumed that the building shell provided no filtering effect for the hazardous agent. This assumption is valid for volatile gases, but for semi-volatile or aerosol agents, the filtering effect can substantially increase the protection factor, as shown by Stearman [5] and Blewett and Arca [11].

2.6. *Habitability of the shelter*

Carbon dioxide (CO_2) and oxygen (O_2) concentrations over time for an occupied shelter were calculated using the lowest measured air flow rate for the shelter inside the test house. The calculations were based on CO_2 emissions of 32 g/h per person [20], a CO_2 concentration of 600 ppm outside the shelter, O_2 consumption of 28 g/h per person [21], and an O_2 concentration outside the shelter of 20.9%. The floor area of the shelter in the test house was 5.0 m^2, and since 0.93 m^2 of floor area per person has been recommended [8], CO_2 and O_2 concentrations were calculated for five persons inside the shelter.

Table 1
Participants in the study

Participant	Gender	Age	Occupation	Test no.	Approximate time to complete task (min)
A	M	35	Technician	1, 10	42
B	F	37	Chemist	2, 12	48
C	F	22	Microbiologist	3	60
D	F	57	Office worker	4	50
E	M	64	Welder	5, 14	40
F	M	38	Network manager	6	30
G	M	28	Chemist	7, 13	55
H	M	48	Technician	8, 15	25
I	F	49	Scientist	9, 11	40
J	M	48	Deliveryman	16	30
K	M	66	Purchasing agent	17	20
L	F	57	Homemaker	18	25
Average					35

3. Results

3.1. Test participants

Information on participants in the study and the approximate time they took to complete the sealing task is shown in Table 1. In the questionnaires that were completed before the experiments, most of the participants indicated that they had some prior knowledge about sheltering in place from the news media, but two participants indicated that they were uncertain about what to do in an emergency before they were given the DHS guidance. After the sealing task was completed, most of the participants indicated that they had no difficulty in completing the task. However, participant B reported having difficulty holding the plastic sheeting in place while cutting and tearing the duct tape, and participant D reported having difficulty in sealing the vent on the rough-textured ceiling, and getting hot in the room with no air circulation. From visual inspection of the sealing after each experiment, it was found that most of the participants performed the sealing correctly according to the DHS guidance. However, participant D left some gaps in taped areas around a partially hidden air outlet grille located at the bottom of the sink cabinet, and participant E failed to seal the same air outlet grille in test 5. All of the participants, except for one, sealed the electrical outlets with tape. Although the DHS guidance did not include an instruction to seal electrical outlets, this measure may be expected to reduce air exchange inside the shelter. Many of the participants also sealed the bathtub and sink drains with tape, but this measure would not be expected to reduce air exchange, because water traps prevent air flow. The average time to complete the sealing task was 35 min.

3.2. Air flow rates

Results from tests conducted during weather conditions that resulted in relatively low air flow rates are shown in

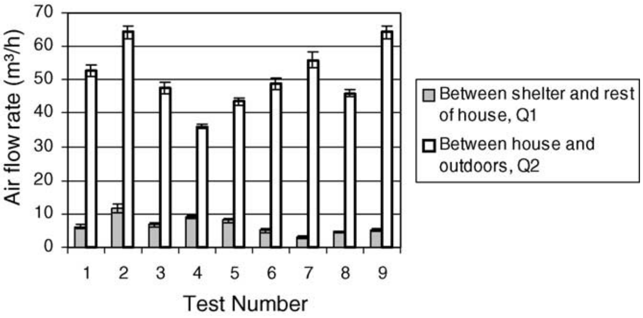

Fig. 3. Results from tests during weather conditions that resulted in low air flow rates for the house.

Table 2
Results from tests during weather conditions that resulted in low air flow rates

Test no.	Ratio of air flow rates, Q_2/Q_1	Inside–outside temperature (°C)	Average wind speed (m/s)	Maximum wind speed (m/s)
1	8.5	0.3	0.89	4.9
2	5.5	0.5	0.28	5.8
3	7.0	0.6	0.44	3.6
4	3.9	−0.2	0.25	1.8
5	5.4	2.1	0.36	3.6
6	9.7	1.9	0.67	4.5
7	17.6	0.9	0.39	2.7
8	10.0	1.0	0.28	1.8
9	12.8	4.5	0.81	4.0
Average	8.9	1.3	0.47	3.6

Table 3
Results from tests during weather conditions that resulted in high air flow rates

Test no.	Ratio of air flow rates, Q_2/Q_1	Inside–outside temperature (°C)	Average wind speed (m/s)	Maximum wind speed (m/s)
10	10.2	16.2	3.6	4.6
11	12.4	16.4	1.2	2.1
12	8.8	19.6	2.3	4.1
13	13.8	13.9	4.9	5.1
14	17.4	15.5	4.3	4.6
15	10.3	16.8	5.0	5.7
16	6.7	12.2	5.0	5.7
17	13.3	13.9	2.7	3.1
18	9.5	18.5	7.1	8.8
Average	11.4	15.9	4.0	4.9

Fig. 3 and Table 2. For each test, the air flow rate between the shelter and the rest of the house, Q_1, and the air flow rate between the rest of the house and the outdoors, Q_2, are shown in Fig. 3. Error bars indicate three standard deviations for the parameters, Q_1 and Q_2, obtained from experimental data, as described above. The average air flow rate between the shelter and the rest of the house was 6.6 m^3/h with a standard deviation of 2.6 m^3/h, and the average air flow rate between the rest of the house and the outdoors was 51.0 m^3/h with a standard deviation of 9.4 m^3/h. The average air flow rate between the rest of the house and the outdoors corresponds to an air exchange rate of 0.17 air changes per hour (ACH). Results for each test are shown in Table 2 for the ratio of the air flow rates, Q_2/Q_1, the difference between inside and outside temperatures, the average wind speed, and the maximum wind speed. Averaging time for the maximum wind speed was 15 s.

Results from tests conducted during weather conditions that resulted in relatively high air flow rates are shown in Fig. 4 and Table 3. For each test, the air flow rate between the shelter and the rest of the house, Q_1, and the air flow rate between the rest of the house and the outdoors, Q_2, are shown in Fig. 4. Error bars indicate three standard deviations for the parameters, Q_1 and Q_2, obtained from experimental data, as described above. The average air flow rate between the shelter and the rest of the house was 14.0 m^3/h with a standard deviation of 3.4 m^3/h, and the average air flow rate between the rest of the house and the outdoors was 150.1 m^3/h with a standard deviation of 13.5 m^3/h. The average air flow rate between the rest of the house and the outdoors corresponds to an air exchange rate of 0.51 ACH. Results for each test are shown in Table 3 for the ratio of the air flow rates, Q_2/Q_1, the difference between inside and outside temperatures, the average wind speed, and the maximum wind speed. Averaging time for the maximum wind speed was 30 min. This averaging time differed from other tests due to an error with the data acquisition system.

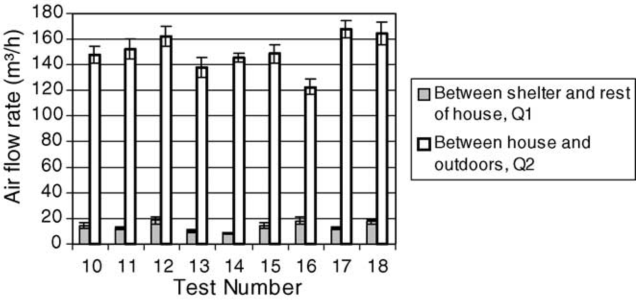

Fig. 4. Results from tests during weather conditions that resulted in high air flow rates for the house.

Results from tests with a technician remaining inside the shelter during measurements are shown in Table 4. For each test, results are shown for the ratio of the air flow rates, Q_2/Q_1, the difference between inside and outside temperatures, the average wind speed, and the maximum wind speed. Averaging time for the maximum wind speed was 15 s.

Results from the three experiments with the bathroom door closed but with no sealing in place showed that the concentration of tracer gas inside the bathroom remained the same as the concentration in the rest of the house. Results from the two experiments with only the bathroom door sealed showed that the concentration of tracer gas inside the bathroom decreased at a more rapid rate than the concentration in the rest of the house.

Table 4
Results from tests with technician remaining inside shelter during measurements

Test no.	Ratio of air flow rates, Q_2/Q_1	Inside–outside temperature (°C)	Average wind speed (m/s)	Maximum wind speed (m/s)
19	7.9	6.5	0.31	3.6
20	9.2	11.4	1.1	4.0
21	4.5	6.7	0.89	3.1
Average	7.2	8.9	0.78	3.6

Table 5
Protection factors for weather conditions with small temperature differences between the indoors and outdoors

Outdoor exposure time (h)	Occupancy time (h)	Protection factor for house			Protection factor for shelter		
		Low	Mean	High	Low	Mean	High
0.25	0.25	35	44	60	314	448	539
	1	5.7	7.1	9.9	17	33	58
	2	3.0	3.6	4.9	5.3	9.1	15
	3	2.2	2.6	3.4	3.1	4.8	7.2
1	1	9.6	12	16	40	77	127
	2	3.6	4.4	6.0	7.2	13	21
	3	2.4	2.9	3.8	3.6	5.9	9.0
2	2	5.1	6.3	8.7	13	24	40
	3	2.9	3.5	4.7	4.8	8.2	13

3.3. *Protection factors*

Protection factors are shown in Table 5 for scenarios that were simulated using the air flow rates measured during weather conditions with small temperature differences between the indoors and outdoors. Protection factors are shown in Table 6 for scenarios that were simulated using the air flow rates measured during weather conditions with large temperature differences between the indoors and outdoors. In both Tables 5 and 6, the outdoor exposure time is the time that the house is exposed to the hazardous agent plume. The occupancy time is the time the occupants remain inside the house or shelter beginning with the arrival of the plume. Low, mean, and high values for the protection factor for the house are based on the high, mean, and low values, respectively, for the measured air flow rate between the house and outdoors. Low, mean, and high values for the protection factor for the shelter are based on the high, mean, and low values, respectively, for the measured air flow rate between the shelter and the rest of the house.

Simulated concentrations outdoors, in the house, and in the shelter are shown in Figs. 5–7 for outdoor exposure times of 0.25, 1, and 2 h, respectively, with an air exchange rate of 0.51 ACH and an air flow rate between the house and shelter of 14.0 m^3/h. Relative concentrations are shown on the *y*-axes in the figures, and the scale is arbitrarily shown as 0–100.

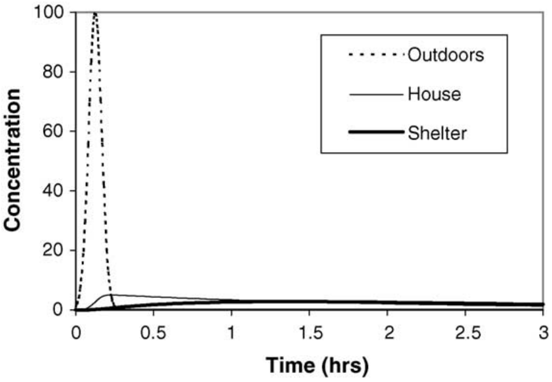

Fig. 5. Simulation for 0.25 h outdoor exposure.

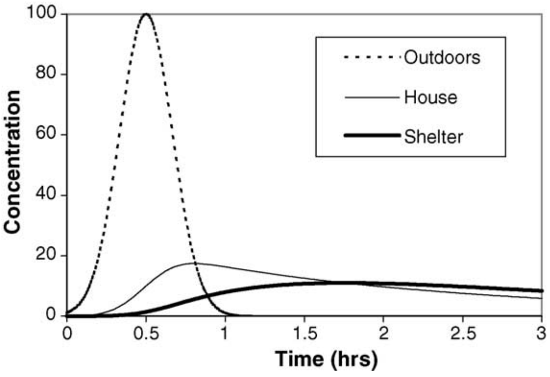

Fig. 6. Simulation for 1 h outdoor exposure.

3.4. *Habitability of the shelter*

As shown in Figs. 8 and 9, CO_2 and O_2 concentrations over time for an occupied shelter were calculated using the lowest measured air flow rate for the shelter inside the test house, 3.2 m^3/h. After 3 h, the CO_2 concentration was approximately 16,000 ppm, and the O_2 concentration was approximately 19.1%.

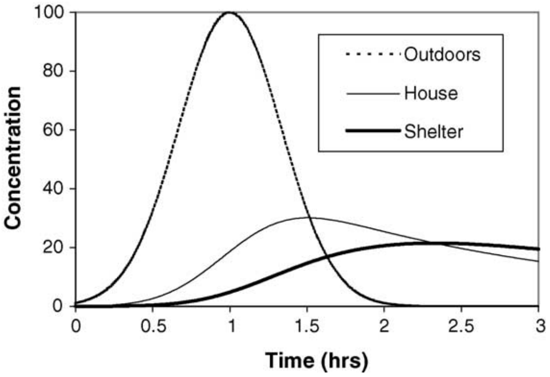

Fig. 7. Simulation for 2 h outdoor exposure.

Table 6
Protection factors for weather conditions with large temperature differences between the indoors and outdoors

Outdoor exposure time (h)	Occupancy time (h)	Protection factor for house			Protection factor for shelter		
		Low	Mean	High	Low	Mean	High
0.25	0.25	14	16	19	122	159	232
	1	2.6	2.8	3.3	5.4	7.0	10
	2	1.5	1.6	1.9	2.1	2.5	3.3
	3	1.3	1.3	1.5	1.5	1.6	2.0
1	1	4.1	4.5	5.4	12	16	25
	2	1.8	1.9	2.2	2.7	3.3	4.5
	3	1.3	1.4	1.6	1.6	1.9	2.3
2	2	2.4	2.6	3.0	4.4	5.6	8.0
	3	1.5	1.6	1.8	2.0	2.3	3.1

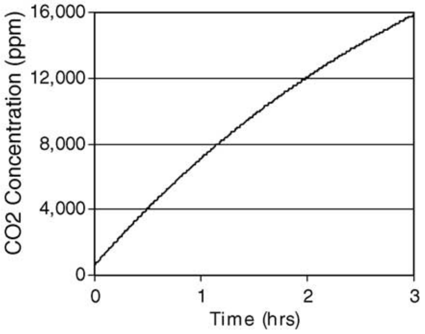

Fig. 8. CO_2 concentration over time for shelter.

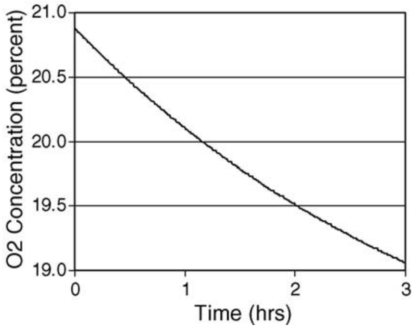

Fig. 9. O_2 concentration over time for shelter.

4. Discussion

4.1. Test participants

As shown in Table 1, men and women of various ages and occupations participated in the study, however, this group of participants was not a statistically valid, representative sample of the general population. Although the educational level of the participants was likely higher than that of the general population, the sealing task was relatively simple, and educational level may not be an important factor. Since the participants were given up to 60 min to complete the sealing task, the approximate times shown in Table 1 may be longer than necessary during an emergency. Rogers et al. [8] measured an average time of 16.7 min to complete sealing of expedient shelters for 12 individuals who were each provided with an "... expedient materials kit tailored to the specific room selected ..." In Table 1, the approximate time to complete the second test was less than the time to complete the first test for most of the participants, suggesting that the time required to implement the expedient measures improved with practice.

4.2. Air flow rates

Variation in the air flow rates between the house and outdoors, as shown in Figs. 3 and 4, resulted from variation in weather conditions. The air flow rate for the house tended to be higher when the temperature difference or the wind speed was higher, as reported in Tables 2 and 3. Variation in the air flow rates between the shelter and the rest of the house resulted from variation in weather conditions and variation in the quality of the sealing. Quality of the sealing was affected by how carefully and completely the participant applied the plastic sheeting and duct tape to areas with air leakage. The air flow rate for the shelter tended to be higher for tests in which problems with the sealing were noted. The variation in the quality of sealing is also indicated by the variation in the ratio of the air flow rates, Q_2/Q_1, as shown in Tables 2 and 3.

As shown in Table 4, the ratio of the air flow rates, Q_2/Q_1, for tests with a technician remaining inside the shelter during measurements was similar to the ratio for tests shown in Tables 2 and 3, and this indicates that slitting the plastic and sealing the opening in the previous experiments did not cause substantial additional leakage.

Results from the three experiments with the bathroom door closed showed that without sealing measures, the bathroom provided no additional protection over the rest of the house. Results from the two experiments with only the bathroom door sealed showed that the bathroom provided less protection than the rest of the house. These unexpected results were likely due to the stack effect of the unsealed bathroom vent. When the door was unsealed, the stack effect drew air from the rest of the house. When only the door was sealed, the stack effect drew more air from the crawl space through leaks in the HAC system ducts and through any leaks in the floor.

4.3. Protection factors

In Figs. 5–7, exposure is illustrated as the area under the concentration curves. Protection factors may be estimated by comparing the area under the outdoor concentration curve to the area under the concentration curves for the house or shelter. Sheltering reduces peak concentrations in all scenarios, but cumulative inside exposures approach cumulative outdoor exposures as the occupancy time increases. The protection factor is maximized if a person remains inside the shelter just until the concentration outdoors is less than the concentration inside the shelter, and then the person leaves the shelter and goes outdoors. If a person remains inside the shelter longer, the protection factor decreases. In a worst-case scenario, a person might be exposed outdoors as a hazardous plume passes over, and then seek shelter indoors after the plume has passed over, further increasing exposure to the hazardous agent.

As shown in Tables 5 and 6, the protection factor increases when weather conditions result in relatively low air exchange rates, such as when the wind speed is low and when the temperature difference between the inside and outside of the home is small. The protection factor decreases when the outdoor exposure duration is longer, and when the time of occupancy is longer than the outdoor exposure duration. The protection factor for the shelter is always greater than the protection factor for the rest of house, but the advantage of the shelter diminishes with longer outdoor exposure times and longer occupancy times. Under ideal conditions, the protection factor for the shelter can be great, but the protection factor can become marginal under less favorable conditions. A comparison of low and high values for the protection factor for the shelter under the same conditions of outdoor exposure time and occupancy time shows that proper sealing can make a substantial difference in the effectiveness of the shelter. If further instructions were included in the DHS guidance, such as an instruction to seal the baseboard to floor area, the effectiveness of the shelter may be increased.

Results show the importance of timing for effective protection. Sheltering in place can be most beneficial if people enter shelters before the arrival of a cloud or plume of hazardous agent, remain inside shelters as the cloud passes over, and exit shelters as soon as the cloud passes. However, sheltering in place can be detrimental if people enter or exit shelters too late. Results imply that sheltering could be more effective if the Emergency Alert System had the capability to inform people when best to enter and exit shelters.

4.4. Habitability of the shelter

As shown in Fig. 8, the calculated CO_2 concentration in the shelter increased to 16,000 ppm after 3 h with five occupants. The National Institute for Occupational Safety and Health (NIOSH) [22] lists a recommended exposure limit (REL) for a time-weighted average (TWA) concentration for up to a 10-h workday during a 40-h workweek of 5000 ppm for CO_2. The NIOSH short-term exposure limit (STEL) for a 15-min TWA exposure is 30,000 ppm. The NIOSH immediately dangerous to life or health concentration (IDLH) for CO_2 is 40,000 ppm. As shown in Fig. 9, the calculated O_2 concentration in the shelter decreased to 19.1% after 3 h with five occupants. The minimum O_2 concentration for safe entry in confined spaces is 19.5%, and the O_2 concentration level where impaired judgement and breathing occurs is 16% [23]. The calculated CO_2 concentration of 16,000 ppm and O_2 concentration of 19.1% might be tolerated by most people for a short time during an emergency, but these concentration levels could affect individuals with respiratory problems. The CO_2 and O_2 concentrations in a shelter could reach more dangerous levels if more occupants were in the shelter, if the air flow rate was lower, if the CO_2 emission rate and the O_2 consumption rate were higher due to activity inside the shelter, or if the time of occupancy was longer.

5. Conclusions

This study evaluated the effectiveness of expedient measures for sheltering in place in residences, as outlined in the U.S. DHS guidance. Plastic sheeting and duct tape were used to seal a room inside a test house by participants who followed the DHS guidance.

An improved method was developed to determine the air flow rate between the shelter and the rest of the house, as well as the air flow rate between the house and the outdoors. Air flow rates were determined from tracer-gas concentration measurements.

Protection factors were calculated for the house and shelter using the measured air flow rates obtained under weather conditions with small and large temperature differences between the indoors and outdoors. Results showed that proper sealing can make a substantial difference in the effectiveness of the shelter. Without any sealing applied, the bathroom used as a shelter in the test house provided no additional protection over the rest of the house. Protection factors were determined for various outdoor exposure times and occupancy times. Protection factors ranged from 1.3 to 539, depending on the conditions.

Results show the importance of timing for effective protection. Sheltering in place can be most beneficial if people enter shelters before the arrival of a cloud or plume of hazardous agent, and people exit shelters as soon as the cloud passes over. However, sheltering in place can be detrimental if people enter or exit shelters too late. Results imply that sheltering could be more effective if the Emergency Alert System had the capability to inform people when best to enter and exit shelters.

The CO_2 and O_2 concentrations inside a shelter are not likely to reach dangerous levels under most scenarios that were evaluated in this study. However, concentrations could reach dangerous levels under certain conditions, such as when many people occupy a shelter, the air flow rate is very low, the CO_2 emission rate and O_2 consumption rate are high due to activity inside the shelter, or the time of occupancy is long.

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