Testing the Effectiveness of Shelter-in-Place for Alternative Release Scenarios

Authors:

Graham E. "Buzz" Harris
URS Radian
P.O. Box 201088
Austin, TX 78720-1088
Phone (512)419-5402
Fax (512)454-8807
Email: buzz_harris@urscorp.com

D. Ray Scott
Safety/IH Manager
Alcoa World Alumina Atlantic
Point Comfort Operations
Phone (361)987-6257
Fax (361)987-6102
Email: ray.scott@alcoa.com

Abstract:

The recent implementation of Risk Management Plans by many facilities has heightened public awareness of the need for protection from accidental chemical releases. Shelter-in-place is the protective measure of choice for most chemical releases. There are case studies in the literature that anecdotally document successful shelter-in-place experiences. This paper summarizes work done on several projects to perform a quantitative predictive evaluation of shelter-in-place for a specific release scenario and a specific shelter.

The data in this paper involves air infiltration measurements to potential shelters. Some of these air infiltration tests were done using the blower-door test, which is a mechanical measure of potential air infiltration. Other tests were done using tracer studies. The usefulness of each type of measurement to shelter-in-place evaluation will be discussed.

Dispersion modeling results can be combined with the air infiltration results to predict indoor concentrations as a function of time. This can be done within some air dispersion models, or it can be done in a spreadsheet using the results from any dispersion model. These approaches will be compared in the paper.

Detailed data on indoor concentrations vs. time can be used to assign a protection rating to the shelter for that particular release scenario. Ratings are based on the peak indoor concentration (as compared to the ERPG-2) and the duration of concentrations of concern. A scaling evaluation can be done in the spreadsheet tool to get some idea of how much larger (or smaller) a release would earn an adequate protection rating.

The paper will draw conclusions about:

- The usefulness of such specific shelter-in-place evaluations;
- The recommended approach for air infiltration testing;
- The preferred approach for indoor air concentration estimates; and
- Lessons to be learned about shelter-in-place in general.

Introduction and Background

Shelter-in-Place (SIP) has been the preferred method for protecting employees and citizens from accidental chemical releases. There have been a number of anecdotal case studies that show that SIP can be effective in protecting human life and health. There has also been some skepticism from environmental groups about the effectiveness of SIP. The recent Risk Management Program communications have made the public more aware of the potential for chemical accidents than ever before. These developments have prompted some initiatives to do testing of proposed shelters in several areas. This paper summarizes some of those test methods and results.

Test Methods

The critical variable in determining the effectiveness of a shelter is the air infiltration rate. All structures have some degree of air infiltration (and exfiltration). Air infiltration is primarily driven by wind and by temperature differences between the inside and outside of a building. Wind creates slightly higher pressures on the windward side of the building and slightly lower pressures on the leeward side. These small pressure differentials cause air to leak into the building on the windward side, and out of the building on the leeward side, through any imperfections in the building sealing. During the heating season, a "stack effect" like the draught on a fireplace chimney will cause warm air to leave the ceiling and roof, which creates a slightly lower pressure in the structure that pulls outside air in through any sealing imperfections. Common leaking areas are around doors, windows, appliance vents, fireplaces, etc.

There are several approaches to measuring or estimating air infiltration rates. The following subsections describe those methods, as well as discussing how air infiltration rates can be combined with atmospheric modeling to estimate indoor concentrations.

Air Infiltration Testing

There are some air infiltration test results in the open literature for various types of residential and commercial structures (see Table 1). These data have been used in the past as general verification of the effectiveness of SIP. Most of these data were generated in energy conservation studies using the blower door test method. These data do indicate that most structures show resistance to air infiltration and should provide protection in a chemical release. The data show some wide ranges for certain types of structures, however, and the same structure could have very different infiltration rates in Norway vs. Texas. These uncertainties in published data led to direct testing of potential shelters.

Table 1. Summary of Published Air Infiltration Rates

Building Type	Location	Test Method	Air Changes per Hour		
			Average	Low End	High End
Typical Residence – Summer[1]	Houston, TX	Blower door	0.92	NA	NA
Typical Residence – Winter[1]	Houston, TX	Blower door	1.11	NA	NA
Typical Residence[2]	Britain	Blower door	1.1	1	1.5
Residential Bedroom[2]	Britain	Blower door	0.87	0.28	2.9
Commercial & Residential Buildings[3]	Florida	Blower door	0.4	0.1	0.9
Office Buildings[3]	Various	Blower door	0.41	0.2	0.7
Residences and Offices[4]	SE Alabama	Tracer Test	NA	0.1	0.4

Table notes:
1. The typical Houston residential data is taken from a paper titled: "Infiltration Testing of Homes in the Houston Gulf Coast Area", by Evan S. Howell, Houston Lighting and Power Company, 1990.
2. The British data are taken from a book titled: ***Loss Prevention in the Process Industries***, by F. P. Lees, published by Butterworth Press.
3. Data taken from the paper "Sheltering Effectiveness Against Plutonium Provided by Buildings", by Rudolph Engelman, Potomac, MD, 1991.
4. The tracer testing in Alabama was taken from a paper titled: "Shelter in Place: The Technical Basis for Its Use in Emergency Planning", by South, B. C., et al, Exxon Co. USA, dated 1993.

Blower Door Testing

The blower door technique (ASTM Method E 1827 - 96, Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door) was developed as an energy conservation tool. The blower door technique involves the use of a variable speed exhaust fan that creates a slight negative pressure in a building while measuring the volume of air flow required to achieve that negative pressure. A building with many large areas of leakage will require a very high air flowrate to achieve any given negative pressure. Conversely, a building with only a few small cracks will require a low air flowrate to achieve that same negative pressure.

The blower door feeds data on differential pressures and flow rates into a computer console. The operator enters descriptive information about the building, such as its name, area in square feet, number of stories, exposure to the wind, climate in the location, and a tightness factor. The computer then calculates the unsealed area and the air change rate for various conditions. The unsealed area is the actual calculated result of the blower door test. The computer then correlates that unsealed area with air infiltration rates expressed as air changes per hour (ACH), and presents an annual average ACH, a summer ACH, and a winter ACH.

The blower door also has the capability of finding the most significant leaking areas. The blower is reversed to create a slight positive pressure on the structure. Each potential leaking area can then be tested using a "smoke gun", which generates a puff of titanium dioxide smoke. Any leak in the area will cause the smoke to move to the leak and out of the room. The speed of movement is an indication of the size of the leak.

The blower door test is standardized, relatively inexpensive ($200 to $500 per test), and gives results on annual and seasonal average bases. The problem with the correlated ACH values is that they are correlated to normal building operation, not to a shelter-in-place condition. Normal building operation means that the HVAC system is running and doors/windows are closed. When sheltering, occupants are instructed to shut down HVAC systems and do extra sealing with duct tape, wet towels under doors, etc. The blower door test does not take these types of conditions into account.

Dr. Cool and Professor Heat did the blower door testing described in this paper under subcontract. They are an HVAC firm located in Dickinson, Texas.

Tracer Testing

Tracer testing is a generic test method that has been used for many types of measurements. Although not a standardized reference method, the procedures are well known and documented. As applied to air infiltration testing, a tracer gas is released inside the shelter and the rate of decay is measured. The tracer gas can be any gas that is stable, non-toxic, and easily analyzed.

The choice of tracer gas is important to the cost and accuracy of the measurements. Helium has been used in infiltration tracer studies in the past, but quantitative helium analyzers are expensive and require extensive operator training. Carbon dioxide (CO2) is also used as a tracer with several advantages:

- It is safe and non-toxic at relatively high concentrations (up to 5000 ppmv);
- It is readily available and inexpensive; and
- CO2 analyzers are available with good precision at reasonable cost.

One drawback against CO2 is that it is naturally occurring in the atmosphere, as well as a metabolic product of human respiration. The same analyzer used for testing the indoor air can be used to establish a baseline outdoor concentration for each test, so the natural occurrence of CO2 in the atmosphere is not a problem. It is best to test shelters that are empty whenever possible to avoid the complications of accounting for human respiration. Some shelters (such as control rooms) must maintain at least one person inside during the tests. A calculation method has been adapted to correct the observed air change rate for the CO2 contribution of human respiration.

The testing done for the projects summarized in this paper used the TSI Q-Trak 5100 Indoor Air Quality analyzer for CO2 measurements. The Q-Trak reads CO2 to the nearest ppm up to about 6000 ppm. It also has the capability to log concentration readings to memory for subsequent analysis. The Q-Trak also measures CO, humidity, and temperature.

The tracer tests begin with a baseline survey of CO2 concentrations outside and inside the building. The shelter is then put into the condition called for by the shelter plan, which includes shutting down the HVAC, closing all doors and windows, and sealing any gross openings (like large return air registers in a door). CO2 is then released in all of the corners of the room, while watching the instrument reading to achieve a well-mixed concentration between 2000 and 5000 ppm. One or more fans are placed around the room to improve mixing. The instrument is then put into logging mode and the room is sealed for a period of 15 to 60 minutes. The instrument logs a CO2 concentration every 5 minutes. At the end of the run, the data are downloaded from the instrument to a computer. The computer calculates the air changes per hour from the dilution rate of CO2 in the room using a spreadsheet program developed by URS Radian. The calculations are a variation on those described in the next section for estimating indoor concentrations based on air changes per hour.

The tracer technique using CO2 is relatively inexpensive and gives air infiltration results that are specific to the shelter situation. One drawback is that the test is a snapshot of the infiltration rates at the time the test was done. The infiltration rates could be higher at other times when winds are higher or the outside temperature is colder.

Estimating Indoor Concentrations

There are two approaches to estimating indoor concentrations for a shelter based on air infiltration rates. One is to use an air dispersion model that includes a feature that allows the user to specify an air infiltration rate, and the program will estimate indoor concentrations. The Cameo-Aloha and SAFER/TRACE models are known to have this feature, and others may have it as well.

Another approach is to use the model of your choice for the atmospheric dispersion in the outdoor air and an Excel spreadsheet, based on a mass balance calculation, to estimate the indoor concentrations. The basic assumptions of the mass balance are that the air inside the room is well mixed, and that there is no change in the total mass of air in the room. If there is no change in the mass of air, then as much air must be expelled from the room as infiltrates into it. The fraction of room volume infiltrating into the room over any given time is given by:

Fraction Exchanged = (ACH) X (Time Step in minutes/60)

The air coming into the room is assigned the concentration of outside air for the subject time after release from air dispersion modeling. The air expelled from the room is assigned the concentration inside the room at the end of the previous time step. The new room air concentration can then be calculated as:

$C_{in\ now} = [FE \times (C_{out} - C_{in\ last})] + C_{in\ last}$

Where:
$C_{in\ now}$ is the concentration inside the room for the subject time period,
FE is the fraction exchanged during the time period,
C_{out} is the concentration outside predicted by dispersion modeling for the subject time period, and
$C_{in\ last}$ is the concentration inside for the previous time period.

This equation is used with the ACH value from either blower door or tracer testing and outside concentration estimates from air dispersion modeling to estimate indoor concentrations as a function of time since release. The calculations are most accurate when performed over a small time step, such as a range of 1 to 5 minutes. This basic relationship can also be solved for FE and ACH if the interior and exterior concentrations at two different times are known, such as in the tracer testing.

Both the dispersion model and spreadsheet approaches yield similar estimates of interior concentrations. The best approach for any given user probably depends on the air dispersion model you prefer. If you like to use a model that has an indoor concentration feature built in, then that will be the easier approach. If you prefer another air dispersion model, then it may be preferable to use the spreadsheet approach. The spreadsheet also allows the user to construct graphs of concentration over time, do scaling analyses, and other special studies that might not be supported in the dispersion models.

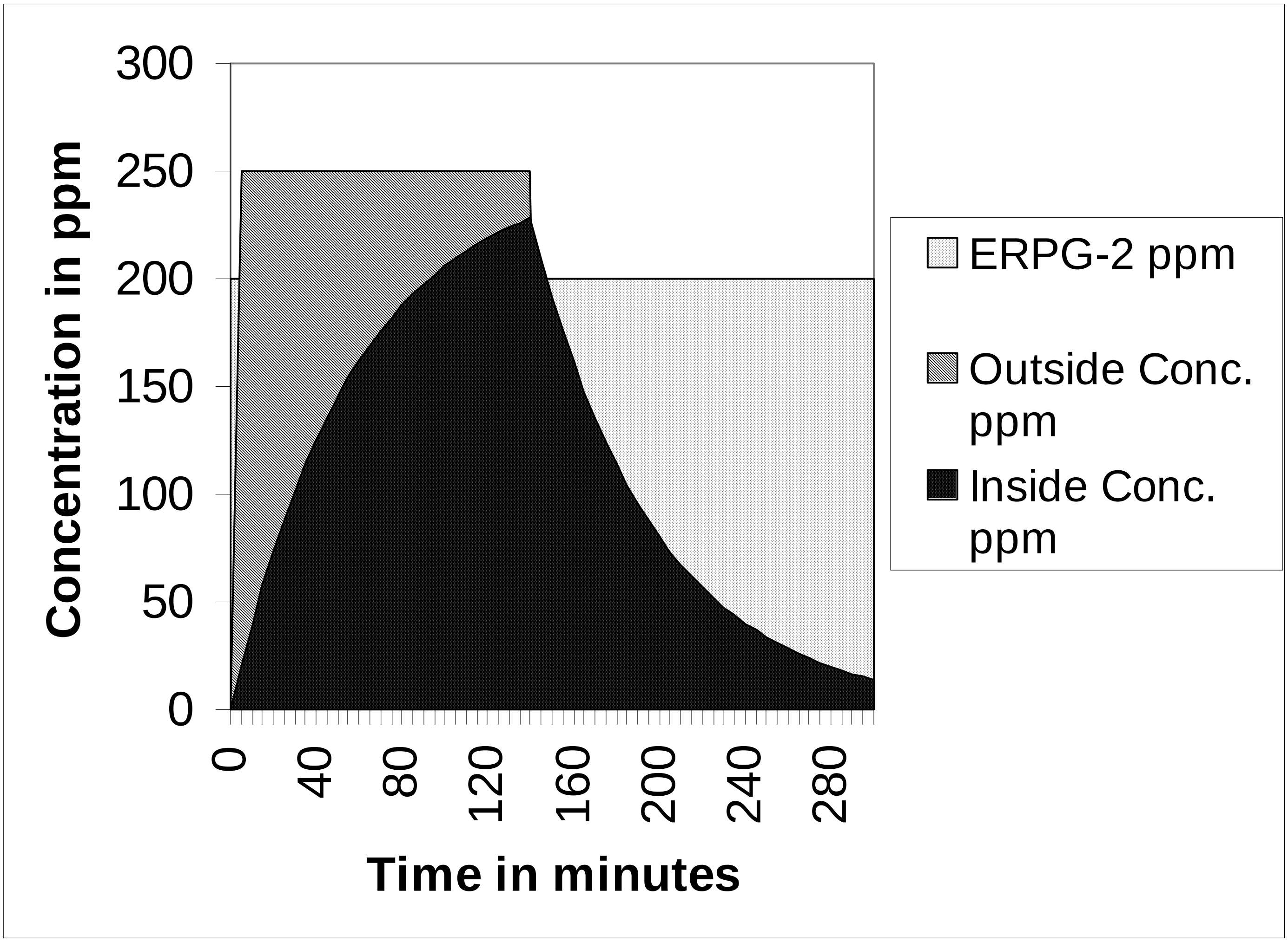
Evaluating Shelter Protection Levels

The level of protection afforded by a shelter is judged by comparing the predicted indoor concentrations to some known health effects threshold. The Emergency Response Planning Guideline-2 (ERPG-2) is the concentration below which a normal person will sustain no severe or lasting injuries when exposed for one hour. A rating scheme can be assigned based on how closely the indoor concentrations approach the ERPG-2:

- Excellent protection – indoor concentration does not exceed 25% of the ERPG-2.
- Good protection – indoor concentration reaches a level between 25% and 75% of the ERPG-2.
- Adequate protection – indoor concentration does not reach the ERPG-2.
- Marginal protection – indoor concentration exceeds the ERPG-2 by no more than 25% and the time above the ERPG-2 is less than 30 minutes.
- Inadequate protection – indoor concentration exceeds the ERPG-2 by more than 25% and/or the time above the ERPG-2 is more than 30 minutes.

It can be helpful to generate a graph of the concentrations to allow an easy visual assessment of the relative approach to the ERPG-2. The spreadsheet allows easy graphing of the outside concentration, the inside concentration, and the health effects levels. See Figure 1 for an example of this type of graph.

Figure 1. Shelter Protection Analysis Graph:
ACH =1, Outside Concentration = 125% of ERPG-2



It should be noted that this protection rating is for a specific release scenario. A shelter might provide good protection against one release, but only adequate for another release where higher outdoor concentrations are reached. The time of exposure issue emphasizes the need for timely all clear signals, since the concentration inside a well-sealed shelter can remain high well after the outside air has cleared.

It is useful to evaluate shelter protection for several different wind directions. Summer and winter prevailing winds can be input to the air dispersion model to estimate outdoor concentrations for these likely wind directions. A “centerline” wind direction can also be modeled, which is defined as a wind that blows directly from the release site towards the shelter. This results in the highest outside concentrations for a given release scenario. These wind conditions apply only to the air dispersion modeling of the outdoor concentrations, not to the measurement of air infiltration rates at different wind speeds or directions.

Results

The author has been involved in testing a variety of structures using both the blower door and the tracer methods. Table 2 provides a summary of the air infiltration measurement results:

Table 2 – Summary of Air Infiltration Results

Structure	**Air Changes Per Hour**	
	Blower Door (Summer)	**Tracer (Spring/Summer)**
Residence – cinder block, 40+ years old, central HVAC, fireplace	0.85	NA
Residence – brick veneer, 40+ years old, central HVAC	0.72	NA
Residence - wood, 40+ years old, central HVAC	0.93	NA
Residence – brick, 2 story, 4 years old, central HVAC, fireplace	0.34	NA
Residential Bedroom - wood, 40+ years old, central HVAC	1.11	0.11
Residence – wood/aluminum siding, 40+ years old	3.22 (whole house)	0.11 (bedroom only)
School – Library	0.45	NA
School – Classroom	0.61	NA
School – Classroom	0.57	NA
Industrial – Lunch Room	1.98	1.94
Industrial – Lunch Room	1.78	0.55
Industrial – Lunch Room	2.65	1.06
Industrial – Lunch Room	2.49	0.89
Industrial – Lunch Room	2.23	0.45
Industrial – Lunch Room	0.73	1.26
Industrial – Control Room	3.86	0.78
Industrial – Control Room	0.86	0.73
Industrial – Meeting Room	1.95	1.02

The structures tested had measured ACH values ranging from 0.11 to 3.86. The school had the best uniform results. The residential structures varied considerably, but most were under 1 ACH. The industrial buildings, most of which were constructed of corrugated metal siding, showed higher air infiltration rates on average.

While these air infiltration rates for specific shelters are interesting, they do not allow the reader to extend the results to evaluate other potential shelters and release scenarios. The spreadsheet described in the estimation of indoor concentrations can be used to examine some generic shelter situations. Table 3 presents data on the maximum protection time for shelters with various ACH values for release scenarios that reach various outdoor concentrations expressed as a percentage of the ERPG-2. The maximum protection time is the time the indoor concentration remains below the ERPG-2.

Table 3. Generic Evaluation of Shelter Protection Times

ACH Values ⎝	**0.1**	**0.5**	**1.0**	**1.5**	**2.0**
Outdoor Concentrations as % of ERPG-2 τ	**Time in Minutes for Indoor Air to Reach the ERPG-2**				
125%	960	185	90	60	40
150%	655	125	60	40	30
175%	505	95	45	30	20
200%	410	80	35	25	15

For simplicity, the outdoor concentrations are assumed to reach the subject concentration and to persist at that level for as long as necessary for the indoor concentration to reach the ERPG-2. In real life, a release may reach a concentration like one of those in Table 3 but not persist long enough for the indoor air to reach a hazardous concentration.

Conclusions

There are several conclusions that can be drawn from the testing and results:

- Air infiltration rates measured are within the range of those values published in the literature.
- Sealing a single room appears to offer a more protective shelter than trying to seal the whole house.
- The tracer test results tend to show a much lower air infiltration rate than the blower door method, even accounting for weather conditions at the time of the tracer test.
- The blower door annual and seasonal average air infiltration rates appear to include some forced outside air infiltration due to HVAC operation, since HVAC systems will be running 90+% of the time on a seasonal basis. This would cause blower door ACH values to over-estimate for SIP conditions where the HVAC is shut down.
- The tracer test results offer the best measure of air infiltration rates specific to a shelter-in-place condition.
- Blower door testing has the ability to identify significant leak points.
- Air dispersion modeling combined with air infiltration testing can provide a site-specific evaluation of a shelter's protection.
- Shelter evaluations are a useful tool that can build confidence in the effectiveness shelters and/or point out areas that need improvements;
- Shelter protection times can vary dramatically depending on the ACH for the shelter and the outside concentration (as compared to a known health effects concentration).

- A well-sealed structure can trap potentially hazardous concentrations inside a shelter for long after the plume in the outside air has cleared to safe levels, which emphasizes the need for a timely all clear signal.
- The construction methods for newer homes show much lower air infiltration rates than those for older homes, and are generally more in the range of commercial buildings.
- There is a wide variation in the air infiltration rates for older homes.
- Key sources of air infiltration in the home include (approximately ordered with the largest sources first):
    - Large unsealed gaps in the ceiling (attic fans, abandoned heater vents, ceiling damage, etc.);
    - Window air conditioner seals;
    - HVAC duct leaks;
    - Appliance vents;
    - Fireplace dampers;
    - Recessed lights;
    - Ceiling fan boxes and other light fixtures;
    - Caulking around windows;
    - Weather-stripping around doors; and
    - Electrical outlets.
- Many of the industrial structure sealing problems arise from the construction design, such as the use of corrugated metal siding and suspended ceilings. The key sources of air infiltration in these industrial buildings were found to be:
    - Poor seal between the corrugated metal siding and foundations or roof beams;
    - Large unsealed gaps in the ceiling (warped or missing ceiling tiles.);
    - Warped and/or poorly sealed doors;
    - Louvers on vent fans in rest rooms that no longer seal when fan is off;
    - Poorly sealed areas where cable trays penetrate walls; and
    - Infiltration through floors for elevated rooms and for rooms with a sub-floor for routing cables.