SHELTER-IN-PLACE STRATEGY: *CONFINE*, AN AIRTIGHTNESS LEVEL CALCULATION TOOL TO PROTECT PEOPLE AGAINST ACCIDENTAL TOXIC RELEASES

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ABSTRACT

Accidental releases occurring in industrial platforms or during transportation of hazardous materials can entail the dispersion of toxic gas clouds. In case of such an event, the best protection strategy for people is to identify a shelter in a nearby building and stay in this room until the toxic cloud has finally been swept off. In addition to seeking refuge in an airtight room, this strategy called "passive shelter-in-place" also includes closing all external openings and turning off all mechanical ventilation systems and openings.
Following the AZF chemical accident (Toulouse, 2001, 30 deaths), a French law was adopted in 2003 that can compel public and private building owners to adopt such a shelter-in-place strategy. To prove that the shelter air-tightness is sufficient and that the occupants will not be exposed to irreversible effects, simulations are required using for instance the modeling tool CONFINE. Originally developed by CETE de Lyon, this software is a pressure code able to model the infiltration of a pollutant inside a 3 zone - building (shelter, attic and rest of building).
This paper aims at giving an overview of CONFINE (governing equations, modeling hypotheses...) and will illustrate its application on one example of shelter-in-place strategy for a public building.
This paper will also present some unexpected results about the impact of wind velocity on shelter-in-place effectiveness. If a higher wind velocity results in a better dilution of the toxic gas outdoor, this situation does not necessarily lead to a lower concentration inside the room, and can conduce to more severe shelter airtightness.

KEYWORDS
Air infiltration, envelope, leakage, shelter-in-place, ventilation, airflow calculation, vulnerability, toxic risk, land-use

INTRODUCTION

Two strategies can be implemented to protect people against toxic risk: shelter-in-place vs. evacuation[7]. In France, shelter-in-place is the sole protective measure recommended, even close to industrial platforms. Following the AZF chemical accident (Toulouse, 2001, 30 deaths), a French law was adopted in 2003. It establishes a new tool around all SEVESO II (high level) classified establishments [9]: the technological risk prevention plan (PPRT) [1]. This local land-use tool specifies in particular protective construction works for new and existing buildings, including implementation of a shelter-in-place system against toxic risk. Such a system includes: 1- general constraints for the whole building design (e.g. system to quickly stop all voluntary airflows) and for a room used as a shelter (minimum size per occupant, presence of sanitary) ; 2- airtightness requirement for this room, with the objective to protect people during 2 hours against irreversible effects[2]. Since 2005, we have been developing the CONFINE software to calculate the minimum airtightness level required for a shelter in order to maintain the internal concentration under a given limit. CONFINE has been designed as a practical tool for operational studies on exposed buildings. It is also used as a research and development tool, to work out regulations and help in decision-makings.

CONFINE'S OVERVIEW: THEORETICAL BASIS OF AN ORIGINAL APPROACH

CONFINE is a pressure code, which considers that each building can be simplified into 3 aeraulic zones (shelter, attic space and rest of the building) delimited by 10 different types of surfaces (Table 1). Each zone is considered having the following homogeneous characteristics: temperature, reference relative pressure and concentration.

Shelter surfaces	Other surfaces
Surface A: outdoor, upwind	Surface F: Attic/outdoor
Surface B: outdoor, at roof	Surface G: Attic/ Building
Surface C: outdoor, downwind	Surface H: Building /outdoor, upwind
Surface D: attic	Surface I: Building /outdoor, at roof
Surface E: building	Surface J: Building /outdoor, downwind

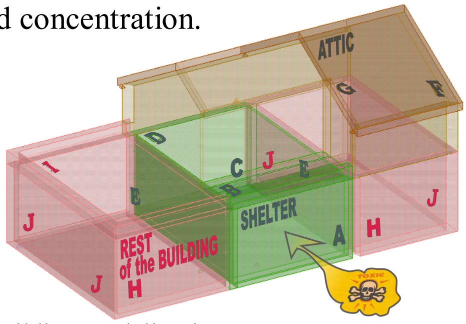

Table 1 and Figure 1 : 10 Types of surfaces used for the building modeling in CONFINE

CONFINE supposes also that all voluntary airflows are stopped and that the initial interior concentration is null. The calculation takes into account climate data, as well as aeraulic and geometric characteristics of the walls. Under these conditions, infiltration airflows are only due to wind pressure and stack effects, according to equations (1) and (2).

$$p_{w,surf,i} = C_{p,i} 0.5 \ \rho_o v_{build}{}^2 \tag{1}$$

$$P(h) = P_0(h_{ref}) + p(h) = P_0(0) - \rho_0 \ g \, h_{ref} + p(h_{ref}) - \rho g \, (h - h_{ref}) \tag{2}$$

$$\rho \approx \frac{P_0}{RT} \tag{3}$$

With:

$p_{w,surf,i}$: wind pressure on surface i (Pa)
$C_{p,i}$: wind pressure coefficient of surface i (Pa). Source: EN 15242 [4]
ρ_o: outdoor air density (kg/m^3)
v_{build}: wind velocity on building (m/s).
P: absolute pressure (Pa)
p: relative pressure (Pa)
g: acceleration of gravity (= 9.81 m/s²)
h: height of a leakage default compared with ground (m)
h_{ref}: reference height of the zone (m),
$_0$: dash referring to atmospheric characteristics
ρ: air density (kg/m^3)
T: temperature (K), T_{indoor} = 293.15 K
P_0: atmospheric pressure in normal conditions
R: universal gas constant (287.055 J kg^{-1} K^{-1}).

Wind velocity impacting the building is based on the meteorological wind velocity (usually measured at 10 m) corrected according to the logarithmical Businger relation [5] with a Monin-Obukov length [6]. This relation takes into account building height, roughness length (relief) and atmospheric stability. This same relation is used by SEVESO industrials for their own previous atmospheric dispersion calculations. Common weather conditions are D5 and F3. The first letter corresponds to the atmospheric stability based on the Pasquill scale (from A: very unstable to F: very stable) while the second figure is the meteorological wind velocity.

Airflows through each surface are calculated using the power law equation (4) and by solving the system (5) of mass balance equations for each of the 3 zones. Results are the 3 reference pressure $p(h_{réf})_i$, from which airflows can be calculated.

$$q_{vl,\Delta Pi,j} = C_{i,j} \, \Delta P_{i,j}{}^n = C_{i,j} < P_{t,j} - P_{t,i} >^n \tag{4}$$

$$\text{For } k = 1,2,3: \quad \sum_{i,j} q_{m,i,j,k} = 0 \tag{5}$$

With:
$q_{vl,\Delta P}$: volumic airflow through an opening with a pressure difference ΔP across it ($m^3.s^{-1}$)
C: flow coefficient of the opening (airtightness defect) ($m^3.s^{-1}.Pa^{-n}$)
P_t: total pressure at both sides from the opening, including wind and stack effect (Pa)
n: pressure exponent. Fixed to 2/3 in CONFINE (-)
$_{i,j}$: subscripts referring to zones at both sides of the opening
$<a>^n$ = sign(a).$|a|^n$ by convention, depending on the direction of the flow
q_m: mass airflow through the opening ($kg.s^{-1}$)

Airtightness of each zone is modeled as a single central path located in the center of each surface listed in Table 1. The flow coefficient of this path C_{ij} is calculated with equation (6), distributing leakage index $Q_{4Pa\_Surf}^{i}$ of the zone or of the adjacent zone proportionately to the area $S_{i,j}$ of this surface. Leakage index of zones "attic" and "rest of the building" are inputs of the CONFINE model: their values are given in tables and quite conservative.

$$C_{i,j} = S_{i,j} * min(Q_{4Pa\_surf,i}, Q_{4Pa\_surf,j}) * (1/4)^{2/3} \quad (8)$$

$$Q_{4Pa\_surf,i} = q_{vl,i,\Delta P=4Pa} \Big/ \sum_j S_{i,j} \quad (9)$$

Once all airflows have been calculated, CONFINE calculates indoor concentration in each zone with the equation (8).

$$\text{For i=1,2,3} \quad V_i \frac{dC_i}{dt} = \sum_j (q_{v,j->i} C_j) - \sum_j q_{v,i->j} * C_i \quad (10)$$

With:
C_i, C_j: concentrations in zones i et j (kg/m^3)
$q_{v,j->i}$: volumic airflow from zone j to zone i (m^3/s)
$q_{v,i->j}$: volumic airflow from zone i to zone j (m^3/s)
V_i: volume of the zone i (m^3)

The limit indoor concentration in shelter, usually the French threshold of irreversible effects, allows to calculate the minimum airtightness level required for the shelter, which is expressed as the air exchange rate at 50 Pa (9).

$$n_{50,i} = \frac{\sum_j S_{i,j}}{V_i} \left(\frac{50}{4}\right)^{2/3} * Q_{4Pa\_surf,i} \quad (11)$$

The tool CONFINE was validated through test cases with CONTAM 2.4b [3].

AN OPERATIONAL TOOL : CASE STUDY WITH A SCHOOL

The school "Pasteur" is located about 1 kilometer away from an SEVESO classified establishment AS. Since 2009, a PPRT constrains such a building to set a shelter-in-place system, in order to protect occupants from a toxic chlorine cloud (Table 2).

Duration (min)	Concentration (ppm)	Wind velocity (m/s)	Atmospheric stability	Outdoor temperature (°C)	Roughness length (m)
60	110	5	D	20°C	0.95

Table 2. Characteristics of the chlorine toxic cloud

A vulnerability diagnostic of the building led to identify a shelter composed of 3 classrooms and a part of a central corridor. It can accommodate all 164 children and adults of the school with all needed characteristics: a floor area of 248 m², more than the recommended 1.5 m² per head; a volume of 960 m^3, more than the recommended 3.6m^3 per head; no external surface directly exposed to the industrial site; only one sanitary and 2 doors should be installed. In the classrooms, closing windows can stop ventilation. Whereas, since the ventilation of sanitary is ensured by a mechanical system, this room requires the installation of additional elements: an emergency circuit breaker and devices to close rapidly the air inlets. Table 3 lists all input data finally used in the CONFINE model.

Surface A,B,D (m²)	0	Surface H (m²)	1359	$V_{rest\ of\ the\ building}$ (m^3)	11821
Surface C (m²)	175	Surface I (m²)	838	$H_{building}$ (m)	15
Surface E (m²)	411	Surface J (m²)	1144	Slope of the roof (°)	0
Surface F (m²)	1122	$V_{shelter}$ (m^3)	960	$Q_{4Pa\_Surf,attic}$ (m^3/h/m²)	30
Surface G (m²)	869	V_{attic} (m^3)	1469	$Q_{4Pa\_Surf,building}$ (m^3/h/m²)	10

Table 3. Input data

To protect people from irreversible effects of chlorine during the 2 hours, indoor concentration in the shelter should stay below 14 ppm. For this shelter in this school, CONFINE calculated that the airtightness level should be lower than $\mathbf{n_{50}=2.3\ h^{-1}}$.

A DEVELOPMENT TOOL: STUDY OF WIND VELOCITY IMPACT

To assess the climate influence on the minimum airtightness required for a shelter, two accidental scenarii are simulated on a building located only 200 m far away the loss of containment. First, the toxic gas cloud atmospheric dispersion is studied using a integral-type model named PHAST, and then the infiltration of the cloud within the building is modeled using CONFINE.

1. Description of the investigated scenarii

The two investigated scenarii are: a pipe failure connected to an ammonia vessel - the pipe diameter is 2" and the vessel is storing 40 ton of ammonia - and a catastrophic rupture of a wagon filled with 60 ton of chlorine. Both substances are pressurized liquefied gases initially stored at ambient temperature (20°C). All input data are listed in Table 4.

Scenario		Scenario a: Failure of the pipe connection on a ammonia storage	Scenario b: Catastrophic rupture of a chlorine vessel
Released product	[-]	Ammonia (NH_3)	Chlorine (Cl_2)
Maximum quantity likely to be released	[ton]	40	60
Product phase	[-]	Liquid	Liquid
Stored temperature	[°C]	20	20
Stored pressure	[bar abs.]	8,5	6,8
Type of release	[-]	Pipe connection failure	Vessel rupture
Orifice diameter	[mm]	50	-
Release height	[m]	1	1
Release direction	[-]	Horizontal	-

Table 4. Input data for the investigated scenarios

2. Investigation on toxic cloud dispersion

Both scenarii result in a two-phase outflow with the emission or "source term" characteristics detailed in .

Scenario		Scenario a (NH_3)	Scenario b (Cl_2)
Released mass flow rate	[kg/s]	11,1	-
Final velocity of the release	[m/s]	221	102
Final temperature of the release	[°C]	-33,4	-34
Released duration	[s]	3600	Instantaneous
Liquid fraction	[-]	0,85	0,84
Mean diameter of the droplets	[mm]	$7{,}3\times10^{-3}$	$2{,}0\times10^{-1}$

Table 5 : Source term" characteristics

The atmospheric dispersion of this "source term" was investigated using the integral-type model PHAST v6.4 supplied by DNV. The integral-type model is based on solving the governing fluid equations on a parametric way. It can handle the atmospheric dispersion of lighter-than-air products, heavier-than-air products or passive products. However, there are several drawbacks in the integral-type model. It assumes that the ground, over which the cloud is dispersing, is perfectly flat and presents a uniform roughness. In addition, the weather conditions are considered invariant during the whole release (in magnitude and in direction).
The toxic cloud profiles concentration that will penetrate the building where is located the shelter were obtained for 3 different weather conditions: D5, D10 and F3. The external temperature is 20°C. The roughness is equal to about 1 m. The results are obtained at 1 m above the ground. All results are summarized in Table 7.

Weather condition	**Scenario a (NH_3)**		**Scenario b (Cl_2)**	
	Maximum concentration (ppm)	Profile duration (s)	Maximum concentration (ppm)	Profile duration (s)
F3	6300	3600	21000	440
D5	4700	3600	24000	180
D10	3580	3600	34000	52

Table 7. Main concentration profiles characteristics 200m far from the accident

Although one should not oversee the possible influence of atmospheric stability, it can be seen that a higher wind velocity tends to increase gas dilution. Yet, it does not necessarily mean that the toxic effects observed on a person located just outside the building will be less severe. This is the case for scenario (a) since the maximum concentration is reduced while the exposure duration remains constant (= 3600 s). But, in scenario (b), since the exposure duration increases while the maximum concentration reduces, due to this longest duration, a person may be more sensitive to lower gas concentrations.

3. Calculation of the n50 of the shelter

The building considered is an individual house with following characteristics (Table 8). The tool CONFINE was used to calculate the maximum n50 required for the shelter. Results are given in Table 9.

Surface A,B,I (m²)	0	Surface G (m²)	100.2	$V_{rest\ of\ the\ building}$ (m^3)	250.5
Surface C (m²)	7.5	Surface H (m²)	37.8	$H_{building}$ (m)	4.18
Surface D (m²)	10.8	Surface J (m²)	69.25	Slope of the roof (°)	10-30
Surface E (m²)	26.3	$V_{shelter}$ (m^3)	27	$Q_{4Pa\_Surf,attic}$ (m^3/h/m²)	30
Surface F (m²)	163.8	V_{attic} (m^3)	97.5	$Q_{4Pa\_Surf,building}$ (m^3/h/m²)	2

Table 8. Input datas

Weather condition	**v_{build} (m/s)**	**$P_{wind,surfaceH}$ (Pa)**	**n_{50} (vol/h) - Scenario a**	**n_{50} (vol/h) - Scenario b**
F3	1.87	1.06	**23**	**11.3**
D5	3.45	3.58	**6.5**	**5.8**
D10	6.90	14.32	**2.0**	**4.6**

Table 9. Maximum n50 of the shelter (in vol/h at 50 Pa)

For this case study, a shelter-in-place system with an "easy to obtain" airtightness requirement for a room, will be efficient to protect people from irreversible effects caused by the dispersion of both scenarii.
In addition, it is important to note that if a higher wind velocity may increase gas dilution in the atmosphere, it can also entail a higher indoor gas concentration, and so, requests a more severe airtightness level for the shelter. In fact, a higher velocity increases the wall pressure on the building, which increases infiltrations (Table 9). Given this finding, and if relevant, it may be worth calculating the airtightness requirement even for the highest wind velocity.

CONCLUSION

In France, the basic strategy of a prevention program to efficiently protect people from accidental toxic clouds is based on sheltering-in-place. In the vicinity of dangerous industrial sites, buildings owners also have to adapt their building with shelter-in-place systems, including an airtight room.

We have developed CONFINE to evaluate the needed airtightness level to maintain in a shelter room toxic concentration under a given limit, usually lower than driving to irreversible effects. This tool can be used as a research and development tool, for guiding regulations and decision-making. For instance, it was used to demonstrate that even if higher wind velocities lead to lower outdoor concentration profiles, they can also increase indoor concentrations. This tool has also been developed as a practical tool for operational studies on exposed buildings. In 2010, the French Ministry for Ecology funded INERIS and CETE de Lyon for developing CONFINE as a free web application and for training private research consultancies, in order to stimulate a market transformation in this field.

Note however that a shelter-in-place system will be efficient only if people know how to use it. Therefore, such schemes should be accompanied by training and communication schemes to raise awareness among the potential end-users.

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[i] Q_{4Pa_Surf} is the airtightness indicator in French Thermal regulation. See Eq. (9).