CONFINE: an airtightness level calculation tool for people's protection in case of accidental toxic releases

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Abstract

Following the AZF chemical accident (Toulouse, 2001, 30 dead), a French law was adopted in 2003 that can compel public and private building owners to implement construction work on their buildings to protect occupants against specific accidents. To face the risk of a toxic gas cloud, they may be obliged to adopt a shelter-in-place strategy which mainly consists of identifying a shelter in the building and remaining 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 air vents.

In order to prove that shelter's air-tightness is sufficient and that the occupants will not be exposed to irreversible effects, simulations are required using for instance the modeling tool named 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, modelling hypotheses,) and will illustrate its application with examples of shelter-in-place strategy for residential and public buildings.
Keywords: air infiltration, envelope, leakage, airtightness, shelter-in-place, ventilation, airflow calculation, vulnerability, toxic risk, land-use.

1 Introduction

Following the Seveso accident in 1976, the European Council adopted the Seveso Directive (EU 85/501/EEC) in 1982. In 1996, the Council Directive

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96/82/EC on the control of major accident hazards, known as the Seveso II Directive, replaced the first directive. Then, in 2003, it was enlarged with the Directive 2003/105/EC. This Directive classifies industrial facilities that manipulate hazardous substances in two categories, high and low level, depending on the quantity of on-site classified substances [1].

Article 12 of the Seveso II requires from local authorities of every Member State, to ensure that appropriate measures are taken to guarantee the protection of people living in areas close to Seveso facilities.

Industrial facilities may entail three kinds of hazards: fires, explosions and toxic clouds. Toxic releases are recognized for their greatest potential to kill, or injure people, on wider areas than fires or explosions. The methyl isocyanate Bhopal catastrophe (1984), entailed more than 2500 dead and injured 10000 people [2, 3].

To protect people against toxic risk, two strategies can be singled out: shelter-in-place (SIP) vs. evacuation [4]. The shelter-in-place strategy consists of taking advantage of the protection offered by buildings against airborne pollutants. The building acts as a barrier that slows down the toxic substance entrance. As a result, the toxic load to which people are exposed inside the shelter can be much lower than outside. The simplest way of sheltering in place consists of closing all external openings, such as doors and windows, turning off all mechanical ventilation systems and closing air vents so to reduce outdoor air entrance. As a consequence, the only way for pollutant entrance is air infiltration through the building envelope leakage.

Analysis of numerous cases shows that the shelter-in-place strategy can be considered as efficient [5]. In France, shelter-in-place is also singled out, even for buildings close to industrial platforms. Since 2003, following the AZF chemical accident (Toulouse, 2001, 30 dead), a French law establishes a new procedure around all Seveso II high-level classified establishments: the Technological Risk Prevention Plan (acronym: PPRT) [6]. This local land-use tool can require protective construction work for new and existing buildings, including implementation of a shelter-in-place system. Such a required system includes general constraints for the whole building design (e.g. fast stop system for all voluntary airflows), for the selected room to be used as a shelter (minimum size per occupant, presence of sanitary), as well as an airtightness requirement for this room. The objective is to protect people during 2 hours against irreversible effects [7].

Since 2005, in order to calculate the airtightness level required for a shelter that will maintain the internal toxic load under a given limit, we have developed the CONFINE software. It has been designed as a practical tool for operational studies on buildings exposed to toxic risk. This software is also used as a research and development tool, to work out regulations and help in decision-makings. After some background on the French requirements for shelter-in-place strategies, we will describe the CONFINE model and analyse its results when applied to a school and 14 individual dwellings.

2 Background about French assessment of shelter-in-place effectiveness

2.1 Building airtightness challenge

Building airtightness is today recognized as an important challenge, especially for low energy buildings [8]. Good quality envelope airtightness enables to better control ventilation airflow rates in buildings. As a result energy needs can be minimized while maintaining a satisfactory indoor air quality. During the last decade, the interest on building airtightness issues in the risk assessment field has also grown, concerning [9–12].

The French industrial risk prevention strategy asks for air leakage requirements for rooms used as shelters, but rarely for air leakage requirements on the whole building envelopes. Those requirements are expressed in air exchange rate at 50 Pa, eqn (1). The flow rate is supposed to respect the power law function, eqn (2). In the French thermal regulation, Q_{4Pa_Surf}, the air leakage index at 4 Pa – i.e., the leakage airflow rate at 4 Pa divided by the envelope area excluding the lower floor – is used, eqn (3). For a building, it is possible to convert both airtightness indicators with a simple formula (eqn (4)).

$$n_{50} = \frac{q_{vl,50}}{V} \tag{1}$$

$$q_{vl,\Delta P} = C.\Delta P^{n} \tag{2}$$

$$Q_{4Pa\_surf} = \frac{q_{vl,4Pa}}{A_{tbat}} \tag{3}$$

$$n_{50} = Q_{4Pa\_surf} * \frac{A_{tbat}}{V} * \left(\frac{50}{4}\right)^{2/3} \tag{4}$$

with:

$q_{vl,\Delta P}$: volumetric airflow through envelope leakage defaults with an induced pressure difference ΔP, between indoor and outdoor ($m^3.s^{-1}$)

C: air flow coefficient of the envelope building ($m^3.s^{-1}.Pa^{-n}$)

n: air flow exponent

V: internal volume of the tested building

A_{tbat}: total envelope area, according to the French thermal regulation

2.2 General methodology for assessment

First step of the prevention strategy consists of defining the PPRT impacted area, based on the safety report supplied by the industrial operator and reviewed by the administration: the report lists of all the possible dangerous phenomena, their probability to occur and the forecast intensity of their effects.

Then, it is possible for public authorities to specify different zones depending on the intensity of the aggression (irreversible, lethal 1%, or lethal 5% effects) and on the types of pollutants. For each zone, a conventional 60 min toxic cloud is also defined. Buildings very close to industrial platforms may be expropriated if the risk is found too high.

At this step, the local land-use plan, named technological risk prevention plan (PPRT), can be published. If the toxic risk is considered too high, the PPRT specifies airtightness requirements for shelters inside buildings. These airtightness levels must guarantee that people seeking refugee will be protected during 2 hours against irreversible effects while the toxic cloud passes away. The PPRT also specifies the conventional toxic cloud to be taken into account, associated with indoor concentration threshold in the shelter.

For non-residential buildings, building's owners have to ask for a modelling study to calculate the corresponding shelter airtightness requirement. To this end, software such as CONFINE can be used.

For dwellings, the methodology is based on abacus. Those abacus allow public authorities to convert the couple {conventional toxic cloud; indoor concentration threshold in the shelter}, expressed through an attenuation criteria, into an airtightness requirement. Airtightness requirements can also be prescribed in the PPRT-plan. We elaborated the abacus with CONFINE [7], assuming that every dwelling can be modelled as a standard 3-zones dwelling with a default envelope airtightness level estimated from the CETE airtightness database (the 95th percentile).

3 CONFINE's overview: theoretical basis of an original approach

CONFINE is a 3 zones pressure code [13]. We consider that any 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 as having the following homogeneous characteristics: temperature, reference relative pressure and toxic concentration.

Table 1: 10 types of surfaces used for the building modelling in CONFINE.

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

In CONFINE we suppose also that all voluntary airflows are instantly 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 the following equations (eqns (5)–(7)).

$$p_{w,surf,i} = 0.5 \;\; C_{p,i}\,\rho_0\, v_{build}^2 \tag{5}$$

$$P(h) = P_0(h) + p(h) = P_0(0) - \rho_0 g h_{ref} + p(h_{ref}) - \rho g (h - h_{ref}) \tag{6}$$

$$\rho \approx \frac{P_0}{RT} \tag{7}$$

with:
$p_{w,surf,i}$: wind pressure on surface i (Pa)
$C_{p,i}$: wind pressure coefficient of surface i (Pa). Source: EN 15242 [14]
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),
$_0$: subscript 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 height) corrected according to the logarithmic Businger relation [15], with a Monin-Obukov length [16]. This relation takes into account building height roughness length (relief) and atmospheric stability. This same relation is used in France by industrials for the atmospheric dispersion calculations they have to produce. Common retained 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 number figures the meteorological wind velocity.

Airflows through each path are calculated using the power law equation, according to eqn (8), and by solving the system of mass balance equations for each of the 3 zones, eqn (9). Results are the 3 reference pressure $p(h_{ref})_i$, from which airflows can be calculated.

$$q_{vl,\Delta P_{i,j}} = C_{i,j}\Delta P_{i,j}^n = C_{i,j} < P_{t,j} - P_{t,i} >^n \tag{8}$$

$$\text{For k =1,2,3:} \qquad \sum_{i,j} q_{m,i,j,k} = 0 \tag{9}$$

with:

$q_{vl,\Delta P}$: volumetric 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: air flow exponent. Fixed to 2/3 in CONFINE (-)
$_{i,j}$: subscripts referring to zones at both sides of the opening
$\langle a\rangle^n$ = sign(a).$|a|^n$ by convention, depending on the direction of the flow
q_m: mass airflow through the opening ($kg.s^{-1}$).

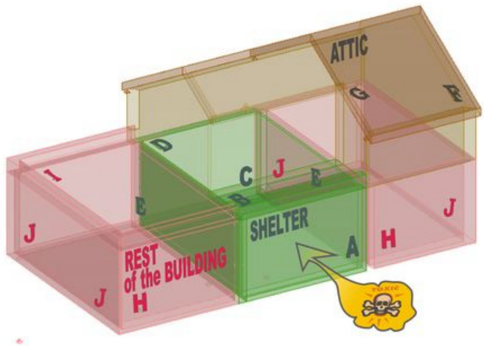

Figure 1: 3 zones and 10 types of surfaces in CONFINE.

The airtightness of each zone is modelled as a single central flow path located in the centre of each surface listed in Table 1. The flow coefficient of this path $C_{i,j}$ is calculated with eqn (10), distributing leakage index Q_{4Pa_Surf} 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 are quite conservative.

$$C_{i,j} = S_{i,j} * min(Q_{4Pa\_surf,i} ; Q_{4Pa\_surf,j}) * (1/4)^{2/3} \quad (10)$$

Once all airflows have been calculated, CONFINE calculates indoor concentration in each zone with eqn (11).

For i=1,2,3 $$V_i \frac{dC_i}{dt} = \sum_j (q_{v,j->i} * C_j) - \sum_j q_{v,i->j} * C_i \quad (11)$$

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 us to calculate the minimum airtightness level required for the shelter, which is expressed as the air exchange rate at 50 Pa (eqn (4)).

The tool CONFINE was validated through test cases with CONTAM 2.4b [13].

4 An operational tool: case studies

4.1 Case study with a school

The school "Pasteur" is located about 1 kilometre away from an SEVESO II 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).

Table 2: Characteristics of the chlorine toxic cloud.

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

A building vulnerability diagnostic led us 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 m^2, more than the recommended 1.5 m^2 per person; a volume of 960 m^3, more than the recommended 3.6m^3 per person; no external surface directly exposed to the industrial site; only one sanitary and 2 doors should be installed. In the classrooms, closing windows will stop ventilation. However, since the sanitary ventilation is ensured by a mechanical system, this room requires the installation of additional elements: an emergency circuit breaker and devices to rapidly close the air inlets. Table 3 lists all input data finally used in the CONFINE model.

Table 3: Input data.

Surface A,B,D (m^2)	0	Surface H (m^2)	1359	$V_{rest\ of\ the\ building}$ (m^3)	11821
Surface C (m^2)	175	Surface I (m^2)	838	$H_{building}$ (m)	15
Surface E (m^2)	411	Surface J (m^2)	1144	Slope of the roof (°)	0
Surface F (m^2)	1122	$V_{shelter}$ (m^3)	960	$Q_{4Pa\_Surf,attic}$ (m^3/h/m^2)	30
Surface G (m^2)	869	V_{attic} (m^3)	1469	$Q_{4Pa\_Surf,building}$ (m^3/h/m^2)	10

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 n_{50}=2.3 h^{-1}. As of today, no work has been realised, so no measurement was performed.

Figure 2: Pasteur School.

4.2 Case study with individual dwellings

We studied 14 individual dwellings located around another SEVESO II classified establishment AS. A PPRT-plan is under elaboration and will constrain such buildings to set a shelter-in-place system, in order to protect occupants from a toxic ammonia cloud (Table 4).

Table 4: Characteristics of the ammonia toxic cloud.

Duration (min)	Concentration (ppm)	Wind velocity (m/s)	Atmospheric stability	Outdoor temperature (°C)	Roughness length (m)
60	3400	5	D	20°C	0.95

Thanks to the abacus [7] realised with the software CONFINE, the public authorities are able to prescribe in the PPRT that shelters in such buildings must respect following airtightness requirements: $n_{50} < 1.5$ h^{-1} if the shelter is upwind compared to the industrial platform, $n_{50} < 6.8$ h^{-1} if the shelter is downwind.

Before any work on buildings, we measured air leakage in rooms identified as shelters in 14 dwellings. Results are summarized in Figure 1Figure 3.

Air leakage measurements were performed through depressurisation method, according to EN 13829 [1]. Results were between 0.9 and 16.7 h^{-1} at 50 Pa.

In 3 cases, it was not possible to find a shelter downwind; as a result there were more severe requirements. Even so, it was respected in 2 cases.

In 4 cases only, the requirement was initially respected, before any work on the shelter envelope.

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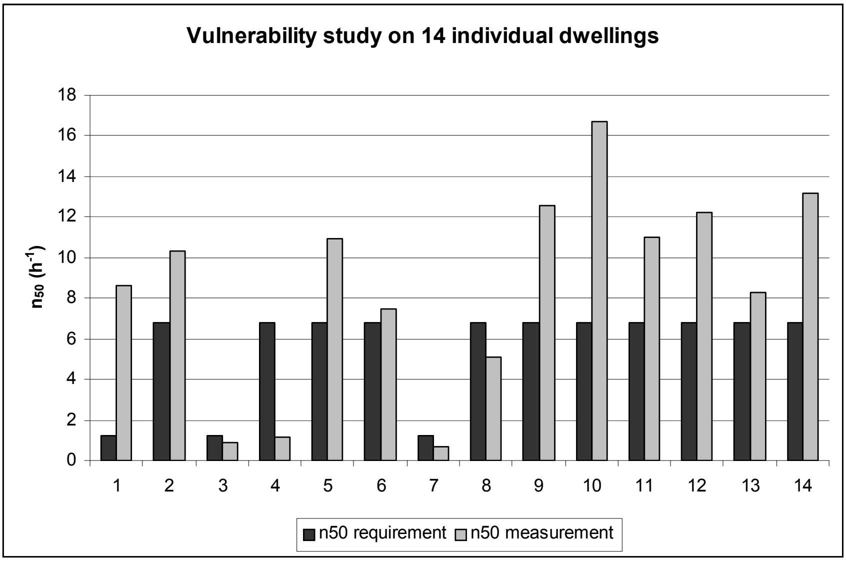

Figure 3: Air leakage measurement.

5 Conclusion

This paper gives a description of the French prevention strategy to protect people from accidental toxic clouds, based on sheltering-in-place. Around all SEVESO II (high level) classified establishments, with high toxic risk, buildings owners have to adapt their building with shelter-in-place systems, including an airtight room.

We have developed CONFINE to evaluate the necessary airtightness level that will maintain toxic load in a shelter room under a given limit, lower than driving to irreversible effects. This tool has been developed as a practical tool for operational vulnerability studies on buildings, exposed to toxic risk. This tool is also used as a research and development tool, for guiding regulations and decision-making. For instance, it was used to elaborate abacus for residential buildings, for which it is also not compulsory to perform modelling studies to evaluate the necessary airtightness level to protect people from irreversible effects.

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 consultancies. It is now used by around thirty consulting companies in France.

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

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References

[1] European Commission: Environment, Chemical Accidents (Seveso II) - Prevention, Preparedness and Response, http://ec.europa.eu/environment/seveso/index.htm
[2] Khan, F.I., Abbasi, S.A, Major accidents in process industries and an analysis of causes and consequences, *J Loss Prevent Proc*, 12, pp. 361–378, 1999.
[3] Vílchez, J.A., Sevilla, S., Montiel, H., Casal, J., Historical analysis of accidents in chemical plants and in the transportation of hazardous materials, *J Loss Prevent Proc*, 8 (2), pp. 87-96, 1995.
[4] Montoya, M.I, Guyot, G., Planas, E., French and Catalan approaches to assess shelter in place effectiveness in the event of a toxic gas release, *Proc. of the 32nd AIVC Conf and the 1st Tightevent*, 6 p., 2011.
[5] National Institute for Chemical Studies, Shelter-in-place as a public protective action, 54 p., 2001, http://www.nicsinfo.org/docs/shelter%20in%20place.pdf
[6] French ministry of Ecology and Sustainable Development, *Technological risk prevention plan (PPRT)-Acting together to control risks*, 3p., 2007.
[7] CETE de Lyon, CERTU, INERIS, Guide PPRT, Complément technique relatif à l'effet toxique, 108 p., 2008.
[8] www.asiepi.eu
[9] Montoya M.I. Pastor E. Carrié F.R. Guyot G. Planas E. 2010. *Air leakage in Catalan dwellings: Developing an airtightness model and leakage airflow predictions*. Building and Environment 45 (6), 1458-1469.
[10] Montoya M.I. 2010. *Contribution to the assessment of shelter in place effectiveness as a community protection measure in the event of a toxic gas release*. Ph.D Dissertation, Universitat Politècnica de Catalunya, Spain.
[11] Chan Wanyu Rengie. 2006. *Assessing the effectiveness of shelter-in-place as an emergency response to large-scale outdoor chemical releases*. Ph.D Dissertation, Lawrence Berkeley National Laboratory. University of California, United States.
[12] Persily, A, Chapman, R.E., Emmerich, S.J., Dols, W.S., Davis, H., Lavappa, P., Rushing, A., Building retrofits for increased protection against airborne chemical and biological releases, NISTIR 7379, 109p, 2007.
[13] Guyot, G., Carrié, F-R., CETE de Lyon, Modélisation des transferts aérauliques en situation de confinement. Bases théoriques et éléments de validation, 38 p., 2009.

[14] EN 15242, Ventilation for buildings. Calculation methods for the determination of air flow rates in buildings including infiltration, 2007
[15] Businger, J. A., Wyngaard, J. C., Izumi, Y., and Bradley, E. F., Flux-Profile Relationships in the Atmospheric Surface Layer, J. Atmos. Sci. 28, 181–189,1971.
[16] Havens, J., and Spicer, T.O., Development of an atmospheric dispersion model for heavier-than-air mixtures (DEGADIS model), Vols. 1-3, University of Arkansas, 1985.
[17] EN 13829: February 2001 – Thermal performance of buildings – Determination of air permeability of buildings – Fan pressurization method (ISO 9972:1996, modified).