a) Title

Assessing health impacts of CO_2 leakage from a geological storage site into buildings: role of attenuation in the unsaturated zone and building foundation

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d) Abstract

Geological storage of the greenhouse gas CO_2 has the potential to be a widespread and effective option to mitigate climate change. As any industrial activity, CO_2 storage may lead to adverse impact on human health and the environment in the case of unexpected leakage from the reservoir. These potential impacts should be considered in a risk assessment process.

We present an approach to assess the impacts on human health in case of CO_2 leakage emerging in the unsaturated zone under a building. We first focus on the migration of the CO_2 in the unsaturated zone and the foundation through numerical simulation with sensitivity analysis. Our results show that the intrusion of CO_2 into a building is substantially attenuated by the unsaturated zone and the foundation and may lead only under very specific conditions (very low ventilated parts of buildings, high flow rate and/or building situated very close to a leaking pathway) to hazardous CO_2 indoor concentrations.

We have then integrated the former results in a global toolbox that provides an efficient and easy-to-use tool for decision support, which enables to assess the impacts on human health of CO_2 leakage from the reservoir to a building.

e) Keywords

Geological storage, Leakage, CO_2, Health, Unsaturated zone, Indoor exposure.

f) Main Text

1 Introduction

Carbon dioxide capture and storage (CCS) is now widely acknowledged as one of the promising mitigation options for reducing atmospheric greenhouse gas emissions. It provides a way to avoid releasing CO_2 in the atmosphere by capturing CO_2 from industrial facilities, transporting it to a storage site and injecting it into a suitable underground geological formation, typically at depth greater than 800 m. The purpose of geological storage is permanent containment of CO_2 (IPPC, 2005).

As any industrial activity, geological storage may lead to potential risks on human health and environment. To be viable, a CO_2 storage project must be environmentally safe and socially sustainable, thus, it must be demonstrated that no significant leak will occur (West et al., 2005). The European Directive 2009/31/EC which establishes a legal framework for the deployment of the geological storage of CO_2, underlines the fact that "*a geological formation shall only be selected as a storage site, […] if no significant environmental* or *health risks exist*" (European Commission, 2009). To ensure this goal, the Directive requires the consideration of numerous criteria for the characterization and assessment of the storage complex. In particular, a risk assessment that considers the effects of leakage on environment and human health must be carried out. A risk analysis should take into account the consequences (*i.e.* the impacts) and the probabilities of occurrence (*i.e.* the likelihood) of unexpected events.

Among the unexpected events, the migration from the reservoir formation to the surface by a preferential permeable pathway (*e.g.* a faulted zone or an improperly abandoned well) has been determined to be one of the most critical risk scenarios because the flow rate may be high in such situations (Lewicki et al., 2007; Oldenburg et al., 2009). To date, most research has focused on the assessment of the CO_2 flow rate that could migrate away from the reservoir (*e.g.* Nordbotten et al., 2009; Pruess, 2011a) rather than on the impacts of such a flow (Price and Oldenburg, 2009). However, the effects of CO_2 depend much more on the level of exposure (defined as a quantity of substance put in contact with the body barriers) than on the total quantity of CO_2 released (Hepple, 2005).

The objective of the present paper is twofold: 1) quantify the impacts on humans of CO_2 leakage from a geological storage site into a building in a more realistic way than what has been done so far and, 2) make the results usable within an integrated risk assessment framework. It is worth mentioning that we focus on impacts and not on risks, since we do not quantify the probability of occurrence (which is likely to be very site-specific).

In the first part of this paper, we investigate the potential health effects of CO_2 (section 2). Then, current approaches to characterize hazardous components migration in the unsaturated zone (*i.e.,* the zone between the ground level and the water table) and intrusion into a building are reviewed in different contexts and in the CCS domain (section 3). After identifying limits of current available approaches, we propose a conceptual model to assess CO_2 indoor concentration and associated hazards resulting from a leakage due to a transmissive faulted zone which emerges at some meters depth under a building (section 4). We first investigate the migration of CO_2 in the unsaturated zone and the foundation through numerical simulation with sensitivity analysis (section 5). In section 6, we discuss these results more specifically regarding the relevance of the considered leakage scenario (likelihood and magnitude) and the assumptions of the modeling procedure. On this basis, we finally show how these results could be integrated in a global, efficient and easy-to-use tool to support decision-making of stakeholders and authorities reviewing risk assessment procedures for CO_2 storage projects.

2 Potential health effects of CO_2

Carbon dioxide is a naturally occurring gas which exists in ambient air in low proportion (about 0.038 % in volume or 380 ppm). It is harmless and even essential to life at low concentration, but it can become hazardous or even lethal at high concentration. Furthermore, carbon dioxide is a color-free gas that cannot be detected by taste or smell below concentration of 10 to 20 % (NIOSH, 1976).

The effects of CO_2 on healthy humans are quite well known. Exposure to CO_2 can be hazardous by two mechanisms: (1) because it reduces the oxygen content of ambient air and thus can lead to asphyxia; (2) because of its own direct toxicity. From Hepple (2005), direct toxicity of high levels of CO_2 occurs before the effects of oxygen lack.

Carbon dioxide behaves as a threshold substance. This means that the effects of its inhalation are entirely defined by a concentration and duration of exposure. From 1 to 3 % CO_2 leads to a decrease of blood pH and a stimulation of respiration. Above 3 %, the breathing rate increases exponentially, hearing loss or visual disturbance may occur. When CO_2 concentration exceeds 5 %, symptoms are more severe and unconsciousness can occur after one to several minutes at concentrations reaching 10-15 %. At level reaching 30 % of CO_2 death occurs within a few minutes.

In France, public authorities have prescribed CO_2 acute toxicity thresholds to be used for industrial hazard studies (Table 1). The "15 minutes Short-Term Exposure Limit Level" of 3 % and the "Immediately Dangerous to Life and Health level" of 4 % are used in the United States (Hepple, 2005). Robinson (2010) considers a cautious "action level" (*i.e.* level above which measures should be taken) of 0.5 % in building.

Table 1 - Thresholds for CO_2 acute toxicity in France used for hazard studies (Ministry of Ecology, 2007).

Thresholds	Corresponding CO_2 level (% vol.)
Irreversible effects	5%
First lethal effects	10%
Significant lethal effects	20%

On natural sites where strong degassing of deep-origin CO_2 occurs, it has been noted that the CO_2 level in soil could be very high (up to 95 % or even more), while in the atmosphere at an elevation of 1 or 2 meters above ground level the CO_2 content is often only twice to thrice the usual concentration (Carapezza et al., 2003; Farrar et al., 1999). Thus, CO_2 is able to dilute rapidly in the atmosphere in open terrain with adequate ventilation. However, because CO_2 is 50 % denser than air (in normal temperature and pressure conditions), it tends to migrate downwards and accumulate in depressions or in confined space potentially creating much higher concentrations (Chow et al., 2009; Benson and Cook, 2005; Bogen et al., 2006). At natural strong degassing sites, human fatalities due to CO_2 have been recorded under particular situations (Carapezza et al., 2003; Holloway et al., 2007; Rogie et al., 2001). Annunziatellis et al. (2003) have shown that a danger may exist for exposure in the basement of houses situated near localized sites where strong natural degassing occurs under specific geological conditions. Human fatalities due to CO_2 have also been recorded in other situations such as work in poorly ventilated space (Louis et al., 1999).

3 Review of current approaches to assess indoor exposure to hazardous compounds.

3.1 Analogies with other domains

In order to investigate the issue of CO_2 intrusion into buildings, we took interest in the literature related to other hazardous compounds for which more data are currently available. Some similarities between CO_2 and volatile organic compounds (VOC) have been established, especially regarding the transport in the unsaturated zone (*e.g.* Zhang et al*.,* 2004). The main difference comes from the consequences on environment and human health, the VOCs being potentially harmful at low concentrations. For these compounds, risk assessment methodologies and remediation measures have been available for more than 20 years (EPA, 1997; Khan et al., 2004). Two main entry mechanisms from underlying soil to indoor air are identified: diffusion or advection through the structural elements or through openings in the structural elements. Diffusion is the result of a concentration gradient between the underlying soil and the indoor air. Advection is due to a difference of pressure between the soil and the interior of the building. Pressure differentials may be caused by numerous mechanisms such as thermal differences, wind, barometric pressure changes or building ventilation (Patterson and Davis, 2009). Field study by Patterson and Davis (2009) show that the molecular diffusion of VOC vapors through the concrete of a slab-on-grade is the dominant intrusion pathway under normal meteorological conditions. However, when the interior of the building is under artificially reduced pressure, their results suggest that the advective vapors intrusion through gaps or cracks in the slab becomes dominant. The authors underline that these results are highly dependent on site specific conditions.

Numerous analytical or numerical models have been developed to quantitatively assess the intrusion of radon[1] or other contaminants into buildings (*e.g.* Améon et al., 2006*;* Andersen, 2001; Johnson and Ettinger, 1991). However, these models are not directly applicable in the case of CO_2 leakage because they use as input data a concentration of contaminant in soil; whereas current approaches for CO_2 calculate a mass flow rate through a flow transport model from the reservoir to a shallow aquifer formation or to the surface (*e.g.* Chang et al., 2009; Pruess, 2008).

Analogies may also be found with CO_2 pollution cases: 1) in case of natural degassing of deep origin CO_2; 2) in buildings situated near reclaimed or abandoned coal mines (Robinson, 2010). However, only few investigations have been made about the characteristics and mechanisms of CO_2 intrusion in this context.

3.2 Critical review in the CCS domain

Two main approaches have been suggested to assess the exposure to CO_2:

1. In case of unexpected migration of CO_2 from reservoir into the atmosphere, numerical dispersion calculations have been suggested in order to assess the exposure level of vulnerable entities in open areas. Simulations of plume dispersion have been performed for point sources of CO_2 such as wells (*e.g.* Aines et al., 2009; Bogen et al., 2006; Chow et al., 2009) and for more dispersed source zones (Oldenburg and Unger, 2004). Several difficulties have been underlined by these studies, especially about taking into consideration the risks of CO_2 accumulation in low-lying areas, the characteristics of the CO_2 source, and the extent of the reservoir footprint.

2. In order to quantitatively evaluate the impact on human health at the Weyburn site, Stenhouse et al. (2009) proposed a conceptual model of exposure to CO_2 into a dwelling resulting from a leakage through an abandoned well. This model converts a flow of CO_2 into an indoor concentration in a very simple way and with few input data (leakage flow rate, volume of dwelling, building ventilation rate) in comparison to the numerical dispersion approach. The calculation of the indoor CO_2 level into the dwelling is based on a mass balance at steady-state conditions. However, this model is overly conservative because it assumes that the CO_2 migrates from the wellhead to the dwelling without any attenuation or resistance during the transport via the upper soil layers or the foundation of the building. It is equivalent to the unlikely situation where a permeable pathway directly emerges inside the building. Furthermore, simulations by Oldenburg and Unger (2003) showed that the unsaturated zone has a potential, although limited, to attenuate a CO_2 leakage due to different processes such as solubility trapping, gas ponding due to CO_2 density, or dilution in soil gas.
   A model considering the transport of CO_2 leaking from a wellhead to a building was suggested by Duguid and Celia (2006). It assumes that the only mechanism responsible for the transport of CO_2 in the unsaturated zone is diffusion. However, simulations carried out by Oldenburg et al. (2010) have shown that both advection and diffusion control CO_2 transport in the unsaturated zone. Thus the model

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[1] Radon is a naturally occurring gas which is present everywhere at the Earth crust. Contrary to CO_2 radon may lead to adverse impact at very low concentration. Very extensive literature is available about the entry mechanisms of this gas into buildings.

suggested by Duguid and Celia (2006) is likely to underestimate the CO_2 intrusion into buildings.

In the present paper, we chose to focus on the second type of approach to assess the exposure in an enclosed (low ventilated) space, CO_2 being more likely to be harmful in such a situation (Oldenburg et al., 2009).

4 Methods

4.1 Proposed general conceptual model

The general conceptual model is presented in Figure 1. We suppose that, due to an insufficient site characterization during site selection or an unexpected behavior of the storage complex, the CO_2 is able to migrate upward and to reach the surface by a leakage pathway. We consider that the leakage pathway is a permeable faulted zone situated under an inhabited area. In sedimentary basins, such as the Paris Basin which could be possible candidate for deep saline aquifers storage (Grataloup et al., 2009), the parent rock is covered by a layer of regolith and soil. Thus, we consider that the leakage pathway does not emerge directly in the house but at some meters below the soil surface. In a zone having an old history of hydrocarbon exploration and exploitation, the leakage pathway may also be an improperly abandoned or an orphan well which has not been mapped during site characterization (Oldenburg et al., 2009). The migration from the reservoir towards the surface could be much more complicated than suggested in Figure 1, because of various phenomena such as secondary accumulation or migration in permeable formations situated on the leakage pathway (Chang et al., 2009; Nordbotten et al., 2005; Pruess, 2008). Furthermore, under the soil layer, the parent rocks are often highly fractured, and thus the migration near the surface is probably more complex than suggested.

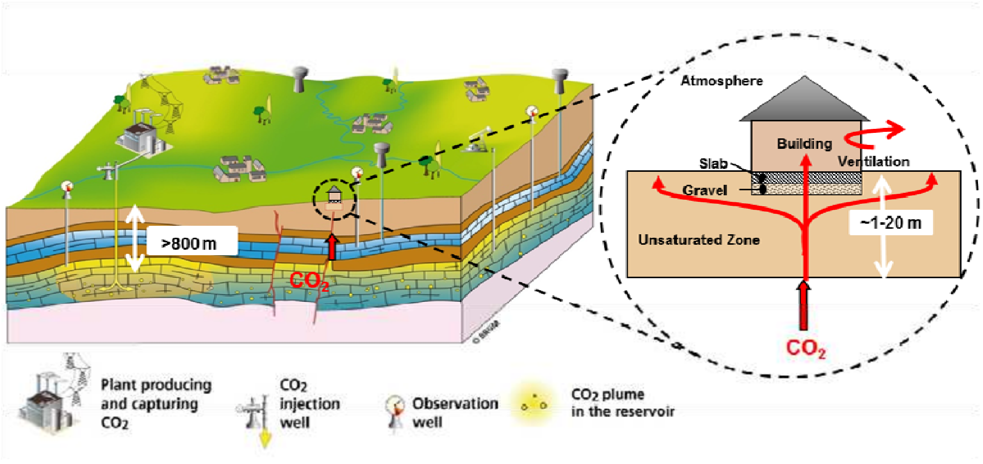


Figure 1 - Conceptual model for CO_2 migration from a reservoir and point-source CO_2 leak in the unsaturated zone under a building.

We focus on what happens when the leaking flow reaches the top bound of a transmissive faulted zone situated some meters under a building. To reach the indoor air of the building, the CO_2 has to migrate in the unsaturated zone and through the foundation. During this migration, several attenuation processes may occur. We propose to study these mechanisms and the associated consequences on human health with the conceptual model presented in the circle of Figure 1. The CO_2 source in the unsaturated zone is situated at some meters depth under a building. The building is a slab-on-grade house whose foundation is composed of a layer of gravel and a layer of concrete. This sort of building is more vulnerable to geological gas intrusion than buildings with crawl-space. The interior of the building is modeled as a global volume with a known ventilation rate. This volume can be considered either as a basement or as a ground-level story, depending on the kind of construction. Note that the CO_2 entry in the unsaturated zone is conceptualized as a point source which is located directly beneath the center of the building: we chose this geometrical hypothesis in order to be in a conservative configuration regarding the CO_2 intrusion. To perform this study, two specific models were successively used: 1) a model of migration of CO_2 in the unsaturated zone that assesses the intrusion rate into the building; 2) a model of exposure which converts the intrusion rate into the building into a volume concentration.

4.2 Model for CO_2 migration and intrusion into the building

We used a numerical simulation approach to simulate the migration of CO_2 through the unsaturated zone and the building foundation considering a large range of configurations.

Simulations were carried out using the multiphase and multi-component simulator TOUGH2 (Pruess et al., 1999) combined with the research module EOS7CA (Oldenburg et al., 2010), which is designed for near-surface applications where the pseudo component air is present (Oldenburg and Unger, 2003).

We used an axisymmetric model for the unsaturated zone and the building foundation, with the symmetry axis in the vertical direction Z passing through the center of the building and the leakage source (Figure 2). The leakage source is at the bottom of the unsaturated zone. Numerical dispersion due to the grid size was found negligible for the simulated time period.

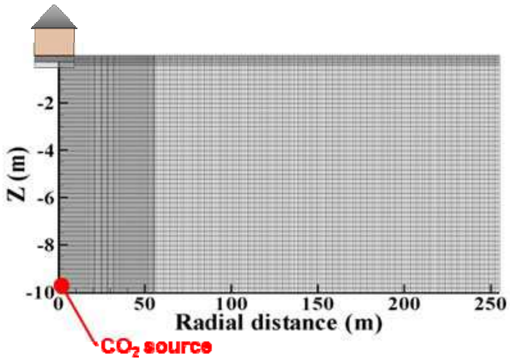


Figure 2 - Mesh used for the base-case simulation. Here with a 10 m thick unsaturated zone.

A constant atmospheric pressure of 10^5 Pa is kept at the top of the system. The lateral model boundary is located at 250 m from the leakage source to ensure that the CO_2 plume is not affected by this boundary, which is held at constant gas-static pressure corresponding to the initial soil moisture-air gravity and capillary equilibrium. In a conservative approach, a no flow condition is used at the bottom of the model in order to force the CO_2 plume to migrate upwards. This hypothesis may be representative of reality if the underlying stratum is made of a parent rock or an impervious layer. The initial state of modeling corresponds to a steady state capillarity-gravity equilibrium obtained through a preliminary modeling.

The other hypotheses of the model are the following:

- The unsaturated zone is composed of homogeneous and isotropic material with no fractures or preferential pathways.
- Temperature is assumed to be constant throughout the model and equals 15 °C.

- The leakage source is situated at the bottom of the unsaturated zone on a 1 m² surface disk with a view to model a point source. We consider that the CO_2 arrives in the unsaturated zone in gaseous state.

4.3 Model for CO_2 exposure in the building

CO_2 entering the building accumulates depending on the ventilation rate of the building. We evaluate the indoor concentration with a simple analytical model based on a mass balance for CO_2 which is extensively used in the area of pollutant intrusion in buildings (*e.g.* Loureiro et Abriola, 1990; UNSCEAR, 1988). Assuming an instantaneous and homogeneous mixing of CO_2 in the building, the CO_2 indoor air level may be expressed as (Eq.1):

$$\rho_{CO2} \times V \times \frac{dC_{in}}{dt} = Q - (C_{in} - C_{out}) \times V \times \rho_{CO2} \times \lambda \qquad (1)$$

Where C_{in} is the CO_2 level in indoor air (% vol.), C_{out} is the CO_2 level in outdoor air (% vol.), λ is the ventilation rate (s^{-1}), V is the volume of the building (m^3), ρ_{CO2} is the density of CO_2 (g/m^3), Q is the intrusion rate of CO_2 into the building (g/s).

Solving this equation at steady state provides the order of magnitude for the indoor CO_2 concentration (Eq. 2):

$$C_{in}(t = \infty) = C_{out} + \frac{Q}{V \times \rho_{CO2} \times \lambda} \qquad (2)$$

In a real condition, the ventilation rate could be subject to important variations within a few hours (UNSCEAR, 1988) due to human activities (opening or closing windows) or meteorological conditions (wind, temperature change, pressure change). Furthermore, the ventilation rate could be contrasted within buildings and within rooms in the same building. The following values (Table 2) are used in this paper (Patterson and Davis, 2009; Stenhouse et al., 2009; UNSCEAR, 1988).

Table 2 – Range of building ventilation rates used in our model.

Ventilation rate (h^{-1})	
Basement	0.13
Building (Low)	0.5
Building (Average)	1
Building (High)	2

4.4 Base case scenario

The hypothetical reference building is assumed to be circular with a floor surface area of 100 m² and a volume of 250 m^3. These correspond to standard values for a building (Andersen, 2001; UNSCEAR, 1988). The thickness of the slab is 0.20 m. Under the slab there is a 0.20 m highly permeable layer of gravel. The building and the unsaturated zone properties in the base case are shown in Table 3. The relative permeability and the capillarity functions are set to different values depending on the considered material (soil; gravel; concrete). The parameters of the van Genuchten (1980) model for the concrete slab are from Monlouis-Bonnaire et al. (2004). The parameters for van Genuchten relation for the gravel layer are set to arbitrary values in order to attribute a lower liquid saturation to the gravel. The diffusion coefficient of CO_2 in the gaseous phase is set to 1.5×10^{-5} $m^2 s^{-1}$ (Oldenburg and Unger, 2003). Intrinsic permeability and porosity for both the slab and the gravel layer are based on Andersen (2001) and correspond to a standard house. The liquid saturation is set to 0.30 for the unsaturated zone in the base case. For the unsaturated zone, the parameters correspond to fine sand.

Table 3 - Properties of the unsaturated zone and the building foundation in the base case setting.

Material	Thickness (m)	Permeability (m²)	Porosity (%)	Capillary pressure, relative permeability
Concrete slab	0.2	10^{-15}	20 %	Van Genuchten; Slr=0.25; Sgr=0.01; $\alpha=10^{-7}$; m=0.5
Gravel layer	0.2	5×10^{-9}	40 %	Van Genuchten; Slr=0.1; Sgr=0.01; $\alpha=10^{-3}$; m=0.4
Unsaturated zone	10	10^{-12}	30 %	Van Genuchten; Slr=0.15;Sgr=0.01; $\alpha=10^{-4}$; m=0.2

A literature review shows that depending on the situation and the modality of CO_2 uprising from the reservoir, the flow rate which reaches the surface following a leakage from the reservoir could be subject to substantial variations. Simulations of leakage through a faulted zone situated near a hypothetical reservoir performed by Pruess (2011a and 2011b) and accounting for self-enhancing and self-limiting effects showed that an order of magnitude for the CO_2 outflow at ground level could be 1 g/s/m². Pruess (2008) used a 1.6 g/s flow rate to study the role of secondary accumulation during CO_2 migration by a fault. Chang et al. (2009) modeled the upward CO_2 migration from fault and attenuation by surrounding permeable layers and found that the flux rate reaching the top of the leakage pathway could range from nearly zero to 70 g/s/m² depending on the situation. A well leakage model used by Oldenburg et al. (2009) for a hypothetical geologic CO_2 storage project leads to a leakage flux rate from 5.10^{-4} to about 5 g/s/m² depending of the permeability of the pathway. However, the maximum leakage flow rate from well with open casing from reservoir to the land surface could be much higher (Aines et al., 2009). On natural sites where deep geological CO_2 is degassing, fluxes measured at ground level can vary from background values (usually less than 1.10^{-4} to 3.10^{-4} g/s/m²) to more than 1 g/s/m² near the vent core (Beaubien et al., 2008; Carrapezza et al., 2003; Farrar et al. 1999).

In the base case setting we chose a leakage rate in the unsaturated zone of 1 g/s (which corresponds to a 10^{-5} /year fractional leakage rate from a 3 million tons reservoir). However we performed a sensitivity analysis to take into account very contrasted situations.

5 Results

5.1 *Base case*

The simulations show that the concentration of CO_2 in the considered building reaches, after 3 months, a steady value which depends on the ventilation rate (Figure 3). The intrusion rate of CO_2 into the building is about 0.17 g/s in the base case. Comparison with the total leakage rate in the unsaturated zone (1 g/s) shows that only a small proportion of the leaking CO_2 enters the building due to attenuation mechanisms that are discussed below. Hazardous levels from Table 1 are not reached in the base case whatever the ventilation rate. Not considering those attenuation mechanisms leads to an indoor concentration above the French irreversible effect threshold of 5 % for the lowest ventilation rate.

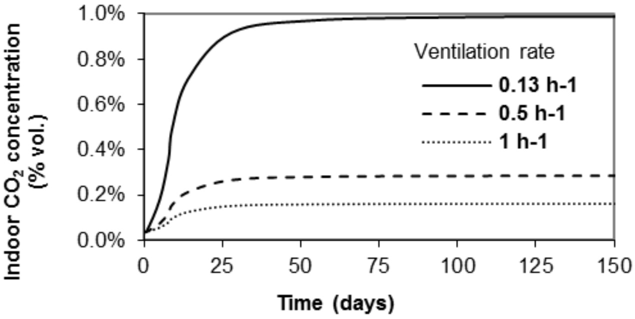


Figure 3 – Concentration in the building as a function of time in the base case for different ventilation rates.

5.2 *Sensitivity analysis*

The CO_2 footprint of storage reservoirs will generally be very large (order of magnitude in the hundreds of km²), and the properties of the unsaturated zone and of buildings in such a wide area are expected to significantly vary. An unforeseen leakage by a fault or an abandoned well may eventually occur anywhere in the footprint of the storage reservoir and thus may occur in very different situations. To be confident that a wide range of situations (including the most deleterious) has been considered, we performed a sensitivity analysis considering a large range of parameters.

From the base case configuration, we performed a single-factor sensitivity analysis based on the OAT technique, which consists in varying one factor at a time to show the influence of this factor (Campolongo et al., 2000). The ventilation rate was set to the lowest value ($0.13\ h^{-1}$) (except for the sensitivity analysis on the ventilation rate). The leakage rate value was kept below 20 g/s in order to avoid excessive pressure build-up in the unsaturated zone. The investigated range of permeability for the unsaturated zone corresponds to soil textures varying from gravel to silt. Very wide ranges of permeability and porosity were chosen to model different slab properties. Results are presented on the "Tornado-type" diagram in Figure 4.

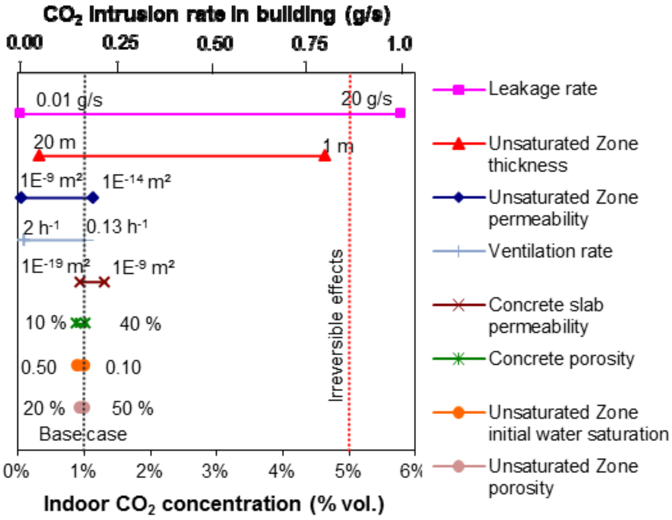


Figure 4 – Results of the sensitivity analysis. The values on the figure are the values of the considered parameters for which the extrema are reached. Note that the scale for the intrusion rate is not applicable for the sensitivity analysis on ventilation rate because in this

particular case the intrusion rate is the same whatever the situation. The French threshold for irreversible effect due to acute toxicity (5% CO_2) is indicated in the figure.

Two main results can be drawn from this sensitivity analysis:

- For the range of parameters used in this sensitivity analysis, the CO_2 indoor concentration varies from nearly zero to about 6 %, which is above the French value for first irreversible effects of 5 %. The Immediately Dangerous to Life or Health level of 4 % is exceeded only for the situations with a low unsaturated zone thickness or a very high flow rate. For all other situations, acute toxicity thresholds are not reached. Therefore, intrusion of leaking CO_2 in low ventilated parts of buildings (basement) may lead, only under very specific conditions, to hazardous situations.
- The most influential parameters on the indoor concentration are ranked based on the width of the variation in the following order: 1) the leakage flow rate; 2) the thickness of the unsaturated zone; 3) the permeability of the unsaturated zone; 4) the building ventilation rate. It is worth noting that we found only a limited number of crucial parameters.

5.3 Dominant CO_2 transport mechanisms

In our simulations, the transport of CO_2 in the liquid phase of the unsaturated zone is negligible compared to the transport in the gaseous phase. The leakage provokes a pressure build-up in the unsaturated zone ranging in the base case (Figure 5a) from a hundred of Pa at one meter depth under the building to about 4×10^3 Pa at the leakage source zone. With a low permeability ($k=10^{-14}$ m²) unsaturated zone (Figure 5b), the pressure build-up is about 4×10^3 Pa whatever the depth under the building. Such variations of pressure are very significant compared to other variations of pressure (due to barometric pumping, thermal effects etc. – cf. discussion in section 6.1) which are known to have strong effects on the intrusion of geological gases. With a high permeability unsaturated zone ($k=10^{-9}$ m²), the pressure buildup reaches only a few Pa close to the leakage source zone (not shown). In this situation, the intrusion in the building is very weak and the resulting indoor concentration is only 700 ppm or 0.07 % (Figure 4) due to a very limited advective migration. In the base case the transport is mainly advective near the source of CO_2 where the pressure build-up is the most significant whereas it is essentially diffusive near the soil surface due to a strong concentration gradient and low pressure gradient (Figure 6). These findings are in agreement with the simulations performed on the CO_2 release test at the Montana site (Oldenburg et al., 2010).

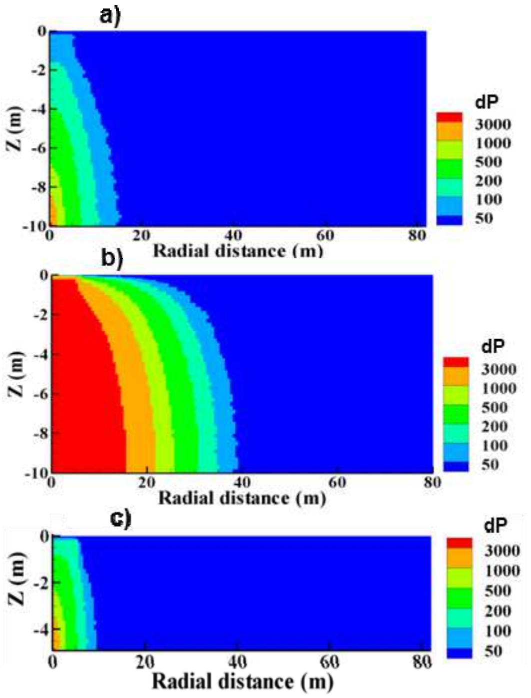


Figure 5 – Pressure increase in the model when a nearly steady state is reached (a) in the base case, (b) with a 10^{-14} m² (silt) and 10 m thick unsaturated zone (c) with a 10^{-12} m² and 5 m thick unsaturated zone; dP is the pressure variation in Pa.

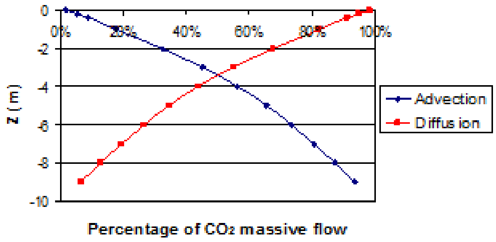


Figure 6 – Advection vs diffusion of the CO_2 as a function of depth at the center of the model in the base case.

5.4 Attenuation processes of the leakage rate

In the base case, the flow intruding into the building is significantly attenuated compared to the flow penetrating the unsaturated zone: only about 17 % of the leaking flow (1 g/s) enters the building. We suggest two main mechanisms to explain this attenuation: 1) the horizontal spreading effect of the CO_2 plume in the unsaturated zone, which enables the CO_2 to bypass the foundation of the building; and 2) the barrier effect of the foundation of the building. The horizontal spreading of a CO_2 plume in the unsaturated zone is a phenomenon that has already been underlined by Oldenburg and Unger (2003). The barrier effect of foundation has been largely studied in the field of pollutant intrusion into buildings because it can have a strong influence on the component intrusion rate (e.g. Patterson and Davis, 2009). We assessed the barrier effect of the foundation through numerical simulations with hypothetical buildings without foundation: it seems to be limited and leads to a less substantial attenuation than the spreading effect. Thus, properties of the foundation are not among the most influential parameters controlling the intrusion of CO_2 (Figure 4).

The spreading effect explains the results of Figure 7: the higher the total flow rate, the larger the plume, and the lower the percentage of the total flow entering the building due to by-passing. Thus, the indoor exposure increases much slower than the leakage rate (Figure 7).

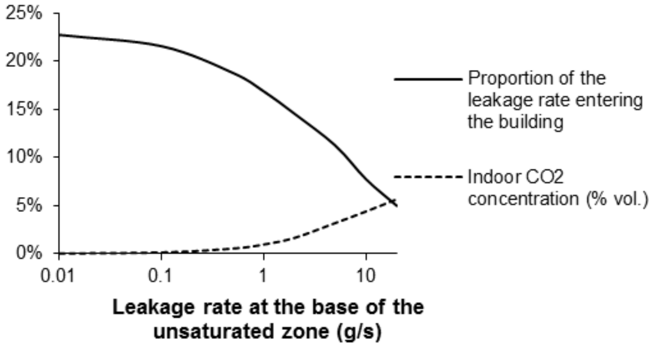


Figure 7 – Influence of the leakage flow rate in the unsaturated zone on the percentage of CO_2 entering the building and on the indoor CO_2 concentration.

5.5 *Influence of the unsaturated zone properties on CO_2 migration*

The permeability of the unsaturated zone also appears to control the intrusion rate. The shape of the plume with contrasted permeability values for the unsaturated zone (assumed homogeneous and isotropic) is shown in Figures 8a, 8b and 8d. In a highly permeable soil, the vertical transport of the plume is limited and the horizontal transport is dominant. Therefore a significant proportion of the flow rate passes around the building and the resulting indoor concentration is low.

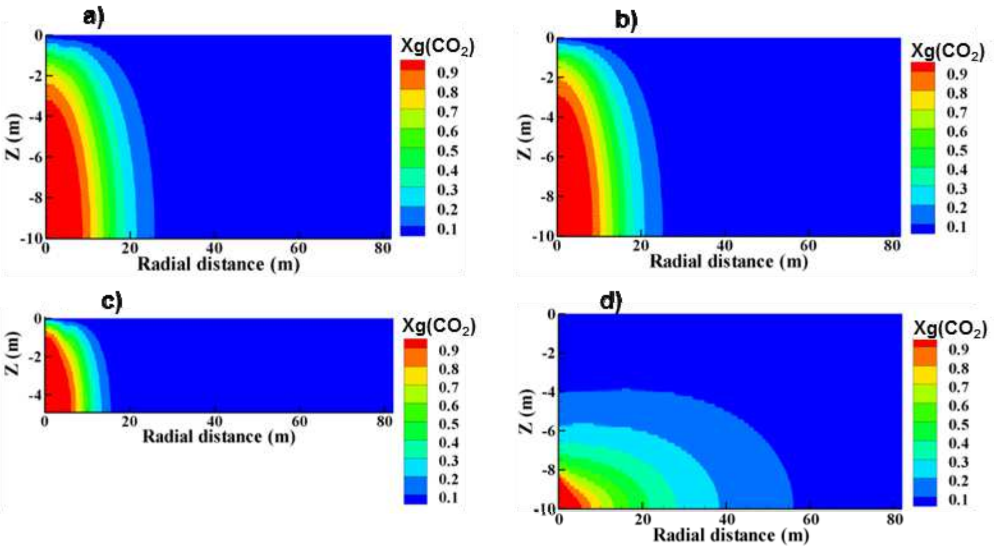


Figure 8 – Plume of CO_2 in the model when a nearly steady state is reached (a) in the base case, (b) with a 10^{-14} m² (silt) and 10 m thick unsaturated zone, (c) with a 10^{-12} m² and 5 m thick unsaturated zone, (d) for a 10^{-9} m² permeability and 10 m thick unsaturated zone. $Xg(CO_2)$ is the mass fraction of CO_2 in the gas phase.

Figure 4 shows that the indoor concentration increases from 0.3 % to nearly 5 % when the thickness of the unsaturated zone varies from 20 to 1 meter. Again, this difference is due to the spreading of the plume in the unsaturated zone: it becomes less important as its thickness decreases. (cf. Figure 8c).

6 Discussion and perspectives

6.1 *Discussion concerning the model*

The choice of our model aims at obtaining a compromise between high consequences / very low probability cases (e.g. orphan leaking well directly emerging in the building as considered by Stenhouse et al. (2009)) and moderate consequences / higher probability (e.g. leakage at hundreds of meters to kilometers form habitations). Thus, this model is less conservative in terms of risk assessment than the one proposed by Stenhouse et al. (2009), however, we consider that this model is still conservative for several reasons.

- The position of the building right above the leakage pathway is the most conservative and does not seem very realistic. Additional simulations should be carried out varying the relative position of the leakage pathway and the building; however the model, assumed axisymmetric so far, should be adapted to that purpose.
- The building considered is a slab-on-grade building, which tends to reinforce the entry of geological gases. Groves-Kirkby et al. (2008) show that other situations such as the ventilated sub-slab configuration significantly reduce the intrusion of geological gases into buildings. Furthermore, in modern slab-on-grade foundation, a polyethylene film prevents the intrusion of gases.
- In our model the pressure in the building is held constantly equal to atmospheric pressure. However, indoor pressure is often a few Pa lower (Andersen, 2001; Johnson and Ettinger, 1991) because of the wind effect and of the “stack effect” due to temperature differences between indoor and outdoor air (Améon et al., 2006). This difference of pressure may lead to an advective gas flow from the soil to the building. However, from Andersen (2001) and Loureiro and Abriola (1990) while the permeability of the soil under the foundation is lower than about 10^{-11} m², the main mechanism of intrusion remains diffusion, so neglecting in our model indoor depressurization and cracks in foundation may, only for the highest permeability soils, lead to underestimating the proportion of CO_2 intrusion into the building.
- From simulation results (Oldenburg and Unger, 2003) and on-field experiments (Robinson, 2010), barometric pumping (due to cyclic natural variations of barometric pressure) may cause local maxima both in the CO_2 flux released from the soil and in the resulting exposure concentration in the atmosphere or in buildings. As barometric pumping is not included in our model, the calculated concentration in the building remains constant after a near steady state is reached, whereas in real situation it should fluctuate with time. Thus, indoor CO_2 exposure could be higher than calculated for short periods of time during rapid drops in barometric pressure. However, Oldenburg and Unger (2003) found that barometric pumping should have negligible effect on the time-average flow of CO_2 which migrates out of the ground.
- We performed some additional simulations to show the influence of permeability anisotropy in the vertical direction to take into account hypothetical soil layering. When the anisotropy factor between radial and vertical permeabilities varies from 1:1 (base case) to 1000:1 the percentage of CO_2 flow entering the building decreases from 17 % to 4 % because of the spreading of the plume in the unsaturated zone.
- Other attenuation processes such as dissolution in a saturated zone or dissolution into the downward infiltrating meteoric water (Oldenburg and Unger, 2003) have not been modeled in our conceptual model. In a real situation, such attenuation processes would decrease even more the percentage of CO_2 entering the building and the resulting indoor concentration. However, if rainfall is intense enough, the compression of soil gases by the wetting front may, by contrast, increase temporarily

the CO_2 intrusion and the indoor concentration (Guo et al., 2008; Robinson et al., 2010).

Moreover, our model is not meant to predict real consequences of a leakage at a CO_2 storage site: the intent is to use it as a first approach to conservatively evaluate what could be the consequences in the case of a leak. As part of an iterative risk management process, risk assessment is used to design appropriate mitigation and monitoring measures. If a leakage pathway is suspected, additional characterization should be performed to properly understand the potential for a leak; the operations should be designed so as to reduce as far as possible the risk of leakage, including programming corrective measures to remediate any detected leak; and a monitoring plan should be implemented to detect any leak before it leads to adverse consequences. We emphasize that a site would not be selected for CO_2 storage if the risk of leakage were found significant. Therefore the consequences computed in our work should not happen; our model is simply one of the tools to be used in this process of assessing the risk related to CO_2 leakage in order to manage it.

Further work is necessary to improve and complete our approach, especially:

- The probability to encounter the modeled scenario leading to hazardous exposure should be assessed. Anyway, in a carefully selected storage site this probability is expected to be very low, as it implies the conjunction of several unlikely circumstances regarding CO_2 leakage and the presence of an inhabited building: (i) the plume has to reach a preferential pathway (faulted zone or abandoned well), (ii) the CO_2 has to migrate along this pathway from depth to the surface in sufficient quantities, (iii) a building has to be built at the top of this conductive pathway (iiii) somebody has to be exposed under specific conditions.
- In the proposed approach, we relied on a One-At-a-Time approach for the sensitivity analysis. The future direction of the present work is to estimate quantitatively the importance of each parameter accounting for the possible interactions and correlations between them with more sophisticated tools for a global sensitivity analysis (*e.g.* Saltelli et al., 2008).
- Our modeling approach would benefit from validation by comparison to fields experiments (*e.g.* monitoring an instrumented building submitted to a CO_2 artificial flow).

6.2 Further developments towards a decision-making tool

The scenario considered above involves different physical phenomena which correspond to different spatial zones:

- Firstly, migration in the saturated zone through a fault or a well (not investigated in this paper);
- Secondly, migration in the unsaturated zone and the foundation of the building;
- Thirdly, accumulation in the building.

In order to use the results presented in this paper in a risk assessment workflow, there is necessity to integrate them in a global tool that compiles various information and knowledge. The need for different process models for the different zones means that it is not possible to carry out a single global simulation from reservoir to ground surface. Therefore we suggest an adequate modular approach (cf. Figure 9) composed of:

- Module 1: CO_2 leakage from the reservoir and migration in the saturated zone through a fault or a well,
- Module 2: CO_2 migration in the unsaturated zone and the foundation of the building,
- Module 3: CO_2 accumulation and exposure in the building,
- Module 4: Exposure to impurities.

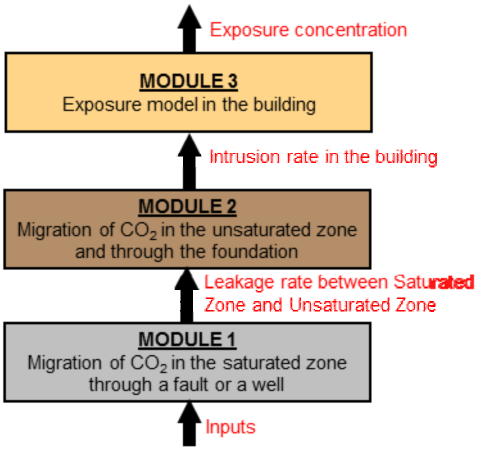


Figure 9 – Proposed segmentation in modules

6.2.1 Justification of the segmentation

The segmentation in “saturated zone”, “unsaturated zone” and “building” may appear obvious given the fact that specific models exist for these different parts. However the relevance of such segmentation with relevant inputs and outputs had to be validated, especially for module 1 and module 2.

Most models concerning the migration of CO_2 plumes in the saturated zone deliver a leakage rate. However, the few meters of soil and the building foundation may behave as a “stopper” and decrease the total leakage rate. This would make the previous segmentation non-relevant, since there would be a feedback from module 2 on module 1.
We carried out an extensive survey based on an analogy between Darcy’s law and Ohm’s law (e.g. Endo et al., 2009) in order to compute a “resistance parameter”. This analytical approach was compared against numerical results and was found to be correct. Using this approach enabled to compare the order of magnitude for resistance in the saturated zone and in the unsaturated zone. Sensitivity analyses were carried out and gave evidence that the resistance due to the unsaturated zone is less, or even greatly less than the resistance in the saturated zone. In a conservative approach, it is then concluded that module 1 and module 2 can indeed be tackled separately and linked together through the leakage rate (output of module 1 and input of module 2).

6.2.2 Module 1: Migration of CO_2 from a geological reservoir through a fault or a well

The development of this module is not the aim of this paper. In order to elaborate a first complete and functional version of the toolbox, we implemented a very simple analytical model based on Darcy’s law. A literature review shows a number of models for the migration of CO_2 in the saturated zone that could be used in order to further develop this first module, in particular: Pruess (2005, 2010), Pruess and Garcia (2002), Chang et al. (2009), Silin et al. (2009), Hayek et al. (2009), Nordbotten et al. (2005).

6.2.3 Module 2: Migration of CO_2 in the unsaturated zone and through the foundation

This module aims at obtaining the intrusion rate in the building given a point source leakage rate a few meters deep below the building, as described above. The results of the sensitivity analysis may be used in order to obtain an accurate value for a known situation. We suggest that a 60% attenuation of the CO_2 flow rate entering the unsaturated zone constitutes a conservative value for assessing a large area containing a high variety of settings.

6.2.4 Module 3: Exposure in the building

The goal of this module is to convert the intrusion rate in the building into indoor air concentration. We use the analytical model presented above (cf. 4.3). More complex models developed taking into account the indoor circulation between rooms and floors may alternatively be used to develop this module. To broaden the field of application of the tool, it may also be interesting to develop a surface module corresponding to free atmosphere based on atmospheric surface-layer advection and dispersion (cf. Oldenburg and Unger, 2004; Chow et al., 2009; Bogen et al., 2006).

6.2.5 Module 4: Integration of a realistic CO_2 stream (CO_2 and gaseous impurities)

Leakage from a geological reservoir is likely to be mostly composed of CO_2. However, the injected CO_2 may contain other components, which we call impurities. Some substances may also be mobilized during the ascent of CO_2.
As shown in Table 4, exposure limits for some gaseous impurities are far lower than for CO_2.

Table 4: Thresholds considered as references for irreversible effects for different gases based on a 30 minutes exposure in France (Baulig et al., 2004; Tissot and Pichard, 2000, 2004a, 2004b)

Component	CO_2	H_2S	NO_2	NO	SO_2
Thresholds	5,00 %	0,010 %	0,005 %	0,010 %	0,010 %

Consequently, regarding health effects, CO_2 may not be the most critical component. Table 5 illustrates that a CO_2 flux from precombustion capture (upper value from IPPC, 2005) may contain 165 times less H_2S than CO_2; since the effect threshold is 500 times greater for CO_2 than H_2S, in a dilution calculation the most penalizing substance would be H_2S.

Table 5: Comparison of ratios concerning maximum exposure concentration and possible composition of injected gas for CO_2 and H_2S

	CO_2	H_2S
Threshold (cf.Table 4)	5% Ratio 500	0.01%
Possible composition of injected gas corresponding to precombustion technology (IPPC, 2005)	99% Ratio 165	0.6%

Studies concerning impurities injected with CO_2 and their possible evolution, or concerning impurities mobilized during the ascent of CO_2 have been carried out (e.g. Jacquemet et al. 2009) but no comprehensive model is currently available.
To take into account these impurities in our tool, we propose an independent module, while making strong hypotheses. We suppose that the leaking flow entering into the building has the same composition than the injected CO_2. This neglects the possible chemical reactions or mobilizations during CO_2 migration in the reservoir and then through upper layers. We also assume that impurities behave as passive gases: due to their low concentrations, their transport is governed by the CO_2 movement.
Based on these hypotheses we calculate a dilution rate for CO_2:

$$Dilution\ Rate = \frac{Concentration\ of\ CO_2\ in\ the\ injected\ flow}{Concentration\ of\ CO_2\ in\ the\ building}$$

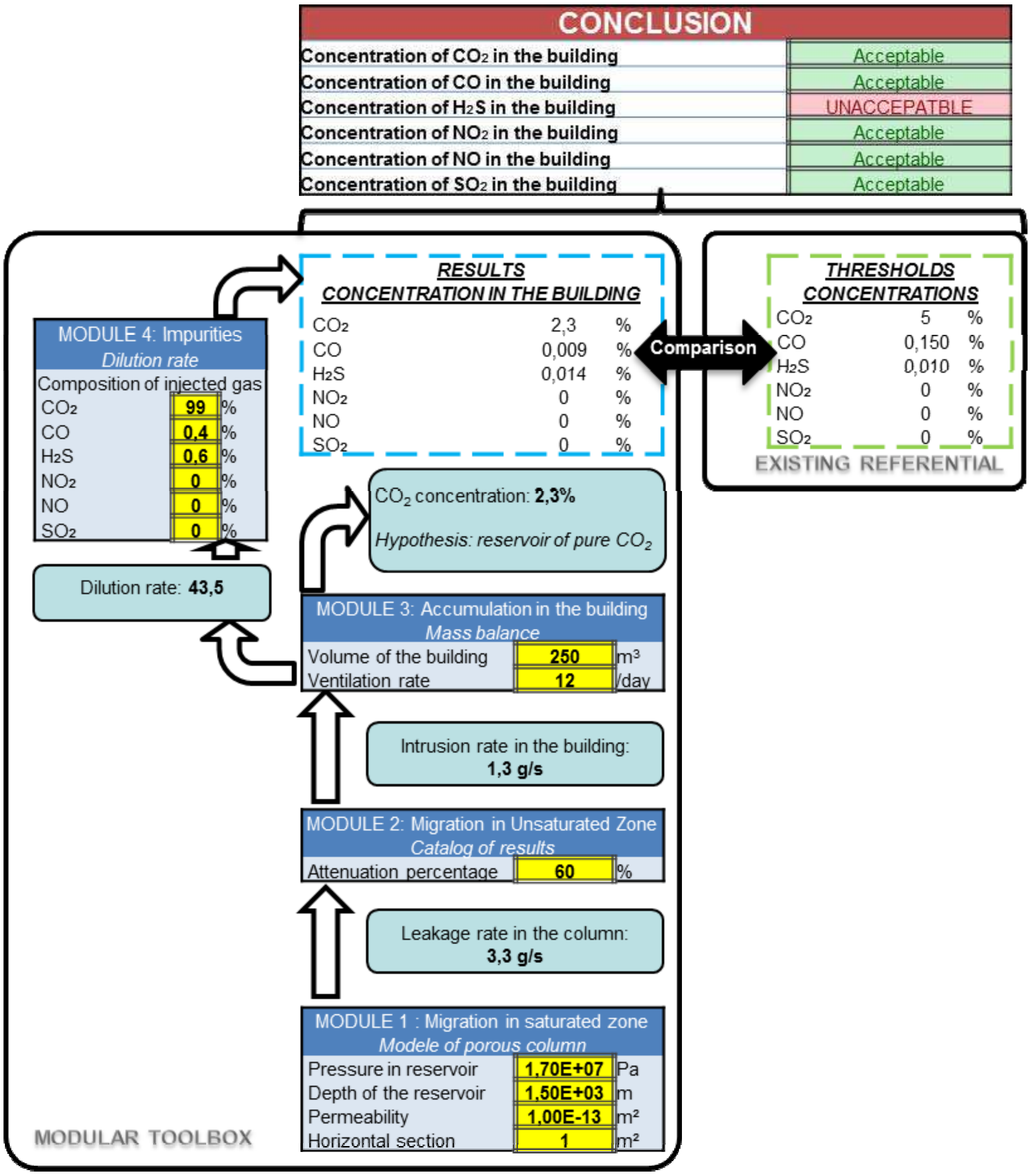
This dilution rate is then used to obtain the concentration of each gaseous impurity:

$$\text{Concentration in the building} = \frac{\text{Concentration in the injected flow}}{\text{Dilution Rate}}$$

This approach completes our model and enables to obtain orders of magnitude, even though it should be improved in the future and gain more integration with other modules.

6.2.6 Presentation of the global toolbox

The aggregation of these 4 modules into a global toolbox provides an efficient, quick and easy-to-use tool for decision support, which can be used to assess the impact to human health of a leak from a CO_2 storage site, with respect to threshold concentrations. In the current development of the toolbox, shown in Figure 10 with values corresponding to a hypothetical site, the user interacts through an interface implemented in a simple calculation sheet by filling yellow cells concerning the parameters of the leakage pathway and the reservoir (Module 1), the attenuation in the unsaturated zone (Module 2), the building characteristics (Module 3), the composition of the injected gas (Module 4). Then, the conclusions of the impact analysis are immediately generated. In the example Figure 10, effects on heath are possible for H_2S, because the injected gas contains significant proportion of this highly toxic gas.



CONCLUSION	
Concentration of CO_2 in the building	Acceptable
Concentration of CO in the building	Acceptable
Concentration of H_2S in the building	UNACCEPATBLE
Concentration of NO_2 in the building	Acceptable
Concentration of NO in the building	Acceptable
Concentration of SO_2 in the building	Acceptable

RESULTS
CONCENTRATION IN THE BUILDING

CO_2	2,3	%
CO	0,009	%
H_2S	0,014	%
NO_2	0	%
NO	0	%
SO_2	0	%

THRESHOLDS
CONCENTRATIONS

CO_2	5	%
CO	0,150	%
H_2S	0,010	%
NO_2	0	%
NO	0	%
SO_2	0	%

MODULE 4: Impurities
Dilution rate

Composition of injected gas		
CO_2	99	%
CO	0,4	%
H_2S	0,6	%
NO_2	0	%
NO	0	%
SO_2	0	%

Dilution rate: **43,5**

CO_2 concentration: **2,3%**

Hypothesis: reservoir of pure CO_2

MODULE 3: Accumulation in the building
Mass balance

Volume of the building	250	m³
Ventilation rate	12	/day

Intrusion rate in the building: **1,3 g/s**

MODULE 2: Migration in Unsaturated Zone
Catalog of results

Attenuation percentage	60	%

Leakage rate in the column: **3,3 g/s**

MODULE 1 : Migration in saturated zone
Modele of porous column

Pressure in reservoir	1,70E+07	Pa
Depth of the reservoir	1,50E+03	m
Permeability	1,00E-13	m²
Horizontal section	1	m²

Figure 10 - Overview of the global toolbox. Input values must be entered in yellow cells. Figures in rounded frames indicate intermediary results (output of the module below, input of the module above).

7 Conclusion

We set up a conceptual model to assess indoor exposure to CO_2 resulting from a leakage from a faulted zone or an abandoned well, which is located beneath a building at some meters depth. The aim of this approach is to assess the health consequences on humans in case of leakage. The probability to be exposed to hazardous concentrations is not assessed, but it is expected to be very low in a carefully characterized, assessed and monitored site.

We performed a sensitivity analysis regarding the migration of CO_2 in the unsaturated zone in order to understand the possible attenuating roles of the unsaturated zone and the foundation. For the ranges of parameters investigated, the indoor CO_2 concentration varies from no effect level to hazardous concentrations. A main finding of this study is that hazardous concentrations are reached in a building only under specific conditions: very low indoor ventilation rate, high flow rate and/or building situated very close to a leaking fault or well. The most influential parameters controlling the indoor CO_2 concentration are the leakage flow rate, the thickness of the unsaturated zone, its permeability, and the building ventilation rate.

The CO_2 leakage flow is attenuated mainly due to the horizontal spreading of the plume in the unsaturated zone with a complementary but weaker attenuation due to the barrier effect of the building foundation. The transport of CO_2 is mainly advective close to the leakage source and diffusive close to the surface.

The main benefit of this model is to assess in a more realistic way than previously suggested approaches the exposure in a building following a CO_2 leakage. A site-specific approximation of the indoor exposure could be easily deduced from the most influential parameters. In the general case, a 60% attenuation of the CO_2 flow rate entering the unsaturated zone is considered a conservative value. Nevertheless, further improvements are necessary especially regarding the control of building-related processes on CO_2 intrusion.

We have integrated these results in a global toolbox, so as to be able to assess the consequences on human of a leakage from the reservoir to the surface. The problem has been segmented in three modules corresponding to the different spatial zones: the saturated zone, the unsaturated zone, the building. Their association delivers the CO_2 content in the indoor air. A fourth module roughly estimates the concentrations of impurities, based on a dilution model. The global toolbox provides an efficient, quick and easy-to-use tool for decision support, which can be used to assess the impact to human health of a leak from a CO_2 storage site.

It is worth mentioning that this toolbox deals with impacts and not with risks: if it were to be employed to assess risk, the impacts should be multiplied by the probability of the event. Benefit could be taken from this computing time efficient tool in a risk assessment process were numerous simulations would be necessary to take into account ranges of uncertainty.

Moreover, such a global tool would be useful for decision-makers in a preliminary risk analysis and would emphasize the most critical points that would require more detailed studies. It could for instance be valuable to help authorities and stakeholders auditing risk assessment studies (Bouc et al., 2009 ; Oldenburg et al., 2009).

g) Acknowledgement

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h) Appendix

i) References

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