From geochemical baseline studies to characterization and remediation of gas leaks: experiences and case studies of the French institute for risk management (INERIS)

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Abstract

Involved in several research projects funded by France and European Union on carbon capture and storage, INERIS has worked for many years on the design, building, testing and field-deployment of gas monitoring devices in soil and subsurface on industrial sites.
INERIS has developed a strong experience using self-designed devices dedicated to the characterization of CO_2 storages and analogues of natural or anthropogenic CO_2-leaking systems.
INERIS focuses on the monitoring of gas flux at surface and on the monitoring of gas migration in the subsurface using gas monitoring wells.

After many years of worldwide research done by many researchers and industrials, it's now time to adopt a "monitoring-ready" approach. That means to be ready to challenge industrial and stakeholders' expectations for efficient, field-deployable and cheap solutions to perform efficient gas monitoring in the soil and the subsurface.

We will here discuss the way INERIS performs surface and subsurface gas measurements (1) to achieve baseline studies on storage sites before injection starts, (2) to ensure monitoring in injection and post-injection phases and (3) to characterize leaking processes that impact surface and urban areas.

Keywords: monitoring ; gas ; leak ; surface monitoring ; vadose zone ; contingency plan ; remediation plan

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1. Introduction

Gas and water geochemistry has a major role to play in the surface and subsurface monitoring of storage sites. See for instance the concern that grew up from 2004 to 2011 about a potential CO_2 leak from the Weyburn-Midale Carbon Capture and Storage (CCS) project in Saskatchewan (Canada) that would be impacting a farm close to the oil-field and force the owners to move from their property [1].

Investigations that were performed to discuss the origin of the “gas anomaly” that was detected in Saskatchewan highlight the need of a good geochemical monitoring plan to help (1) to define baselines before any CO_2 injection starts, (2) to track gas leaks that could impact surface and (3) to re-establish public confidence in the feasibility of safe carbon storage.

Through our own experience and feedback, we will here discuss:

- The monitoring devices and the monitoring strategy that have to be considered to establish baselines before injection starts and to perform good surface and subsurface gas monitoring injection and post-injection phases;
- The characterization of CO_2 leaks and the understanding of the gas migration dynamics in the subsurface, introducing the buffer role that could play the unsaturated zone (or “vadose zone”) as a very last barrier before CO_2 reaches surface and accumulates in buildings, tunnels, underground car parks, cellars…

Discussions will be based on our involvement in research and industrial pilot sites but also on study of a leaking system in a former mining area.

Working on CO_2 leaking analogues (e.g. volcanic area) is very insightful and challenging in a scientific and technical point of view, because we face conditions that cannot be encountered on industrial sites unless in accidental context. But we must handle the analogy with care and be aware of its limits… by also working on industrial or research pilot sites.

2. Performing surface and subsurface gas monitoring above CO_2 storages

INERIS is involved in the monitoring of an industrial CCS pilot site for several years. We have taken part in the baselines studies and take now part to gas monitoring during injection phase, by:

- Performing gas flux measurements at surface (soil/atmosphere interface) [2;3];
- Characterizing gas migration processes in the subsurface (~100 meters depth) through gas concentration measurements in the gas phase of a monitoring well [4].

2.1. Surface monitoring using gas flux measurements

INERIS monitors CO_2 flux above the industrial storage site since September 2008 by using a patented accumulation chamber (fig.1). Monitoring is performed quarterly on 35 locations. Numerous field measurement campaigns have been held today. Some of them have been held before injection starts (= baseline studies) [5].

As comparison, gas flux measurements have also been performed in other locations in France far from a CCS site. These measurements are done since several years on 12 different locations situated along 2 long geographic profiles (profile A: N-S and profile B: W-E, see map on fig.2 right). They constitute a database giving a range for CO_2 natural fluxes emitted at surface by (micro)biological and pedogenetic activities in soil that are usually observed in France all over the country for different land use contexts (forest, meadow, agricultural field... see fig.1 left). This range is from 0 to 18 $cm^3.m^{-2}.min^{-1}$ (0 to 54 10^{-8} $kg.m^{-2}.s^{-1}$). Results show a strong relation between CO_2 flux value and seasonal weather conditions. Atmospheric temperature seems to be a key factor controlling gas emission at soil-atmosphere interface (fig.2).

Any other significant contribution to CO_2 emission at soil-atmosphere interface such as a CO_2 leak from a deep storage would increase the quantity of gas that is emitted by biological and pedogenetic activities in soil and would then be theoretically detected.

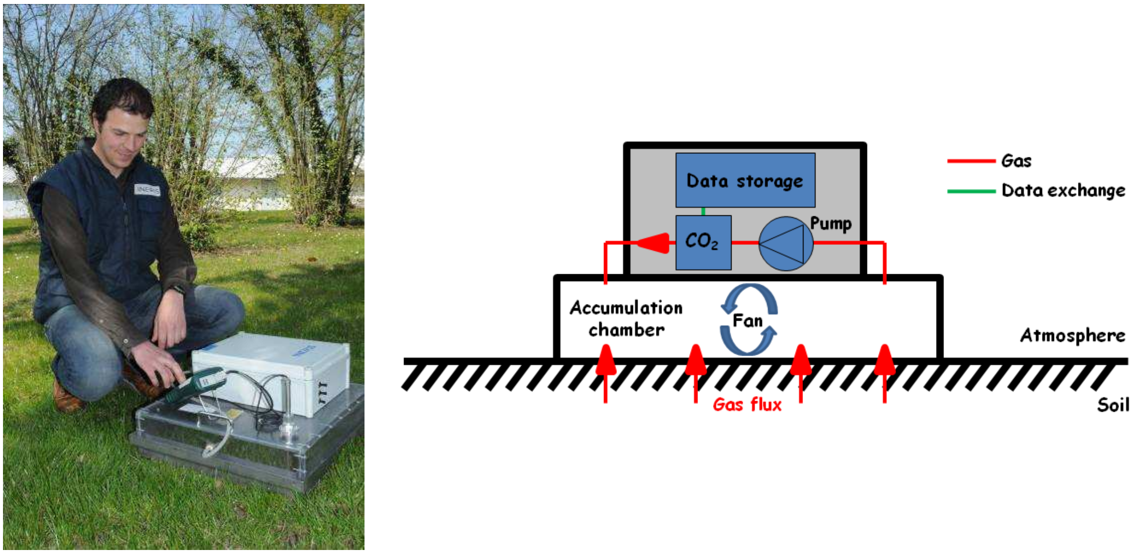

Fig. 1. Performing gas flux measurements at soil-atmosphere interface using an accumulation chamber

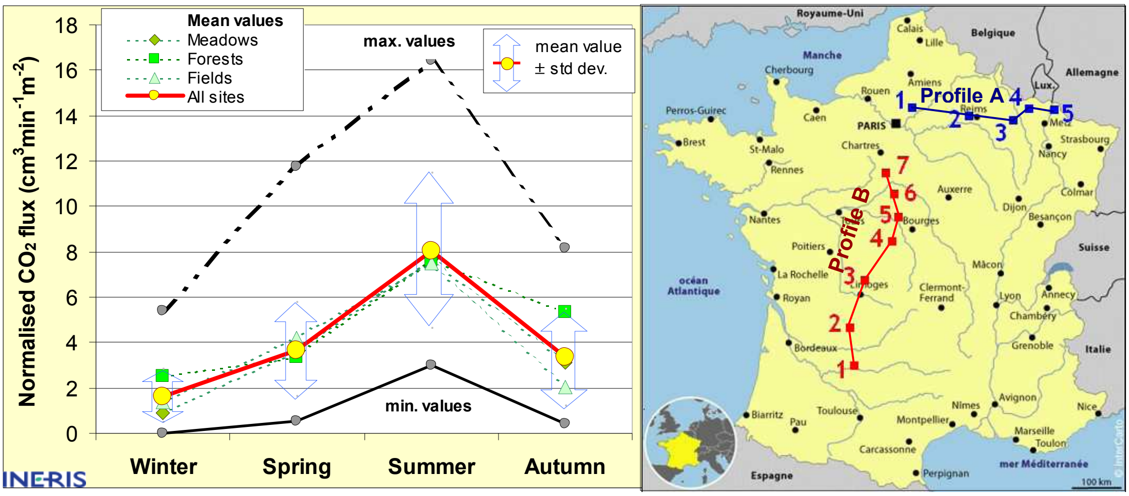

Fig. 2. Natural CO_2 emissions at soil-atmosphere interface depending the season and the land use context
(statistical data of gas flux measurements performed in France on 12 locations along 2 geographic profiles during more than 5 years)

Gas flux measurements at surface have an important role to play in the monitoring plan of a CCS site because:

- It is a direct and very flexible monitoring method that can detect any significant anomaly in time as long as measurements are regularly performed and statistically workable;
- It is a light and fast monitoring method to quickly confirm or remove any doubt concerning the occurrence of a gas leak from storage at surface;
- It is a method that can be easily coupled with other measurements performed in soil such as gas soil measurements or isotopic analysis of the emitted gas;
- It is a helpful communication tool to establish public confidence in the safety of CCS project (this is a direct method which is visible and whose physics is easily understandable).

2.2. Subsurface monitoring using dedicated wells

Before reaching surface, gas leak from CO_2 storage will migrate through upper geological formations. Knowledge of underground residence time and processes that can impact this migration is fundamental to determine the potential consequence of a leak at surface.

INERIS works for several years on the characterization of gas migration processes in the unsaturated shallow formations (vadose zone) because these formations are the last barrier before gas reaches surface (see section 3 for a concrete example).

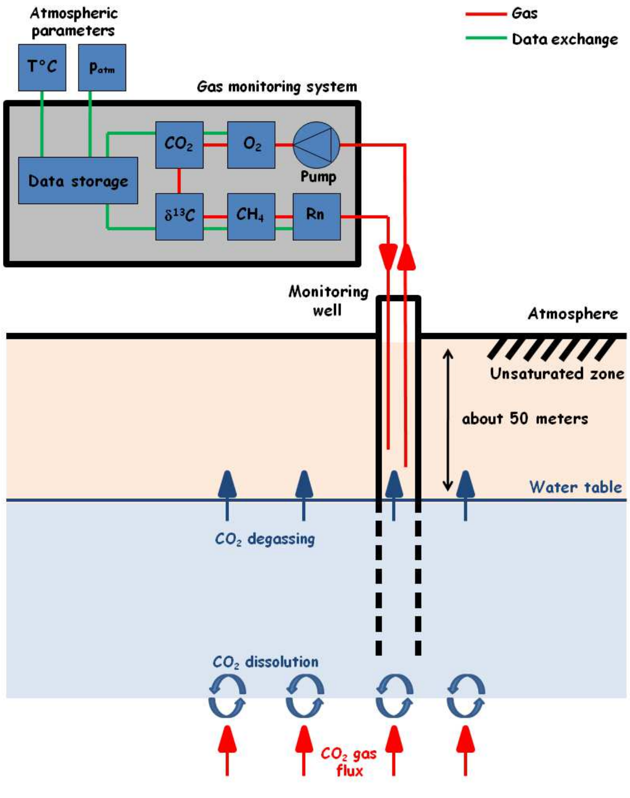

Fig. 3. Performing gas monitoring in the subsurface using a monitoring well

As field case study, a monitoring well has been drilled close to the injection well of the CCS pilot site. This well was drilled down to about 100 meters depth and has reached water table at about 50 meters depth. Before reaching surface, a CO_2 leak from storage would migrate through the aquifer formation and eventually be dissolved in water. Degassing processes at water table could then occur and lead to CO_2 emissions in the vadose zone and at surface (fig.3).

INERIS is monitoring gas concentrations and carbon isotopic signature in this well since several years. Atmospheric parameters (atmospheric temperature and barometric pressure) are also monitored. Measurements began before injection starts.

Aims are to better understand gas exchange dynamics between saturated and unsaturated zones and detect any potential anomalous gas migration towards surface.

Monitoring gas migration in subsurface has to be taken into account when drawing monitoring plan of CCS site because dynamics of underground gas exchanges can have a strong effect on gas emission at surface.

In some extent, underground porous media can constitute buffer volumes that accumulate gas (in dissolved or gaseous phases. When a change of the weather conditions occurs (for example a change of the atmospheric temperature but also of the barometric pressure as we will see in the section 3), the gas is released and can migrate towards surface.

3. Characterizing CO_2 emissions at surface in order to propose adapted remediation solutions

Since 2009, INERIS conducts research to understand production and migration processes of CO_2 in the vadose zone above a former underground mining area.

CO_2 emissions have been detected in urbanized areas at surface or in cellars. These emissions can expose people to O_2-defficient and CO_2-enriched air which can be hazardous (risk of unconsciousness or asphyxia) [6].

Even if there is no underground storage in this area, the context is very similar to what industrials could face in case of gas leak from CO_2 storage. We will see that feedback from this case study is very useful to help to draw remediation and contingency plans for CO_2 geological storages.

When gas emissions are detected at surface, a fast characterization has to be done to assess risks to people and if needed suggest emergency solutions.

This characterization should aim (1) to determine gas production mechanism or gas origin, (2) to identify migration pathways (diffuse or located emissions) and (2) to describe dynamics of the emissions (driving force and time variations). Results will influence content of remediation and contingency plans. Special attention should be paid to administrative authorities, inhabitants and press that can put pressure on people working on the characterization emissions to find out results and to design solutions.

All measurements that have been performed by INERIS at surface and in the subsurface are listed and described in table 1.

Table 1. Measurements performed to understand production and migration processes of CO_2 in the vadose zone of a former underground mining area

Aim	Measurement	Protocol
Determination of gas production mechanism or gas origin	CO_2 concentration	Measuring CO_2 and major gas concentrations in atmosphere of close spaces at surface (e.g. cellars) or in soil gas to detect any change of abundance.
	Isotopic analysis	Measuring the carbon isotopic signature of CO_2 to determine the gas origin [4].
Identification of migration pathways	Gas flux at soil-atmosphere interface	Performing CO_2 flux measurements at surface using an accumulation chamber in order to map emissive areas.
	Volume activity of radon	Monitoring volume activity of radon in gas emissions at surface to have clues on migration pathway and duration.
Description of dynamics of gas emissions	Gas pressure	Monitoring pressure gradient between underground and surface with pressure sensors to see if it can be a driving force of gas emissions.
	Gas temperature	Monitoring temperature gradient between underground and surface with temperature sensors to see if it can be a driving force of gas emissions.
	Gas flow	Monitor gas flow direction at highly emissive points (such as cracks, faults, wells…)

Results show that CO_2 can be produced by a geochemical process in the capillary fringe between saturated and unsaturated zones (at ~50 meters depth, see fig.4). CO_2 accumulates in vadose zone and migrates later towards surface in low barometric conditions (sudden barometric pressure decreases are here the main driving force, see fig.5). CO_2 preferentially migrates through the numerous cracks that are generally present on the whole extent of the former mining area. Usually hidden/covered by soil layer, cracks are not easily detectable unless gas anomalies have been already detected above them.

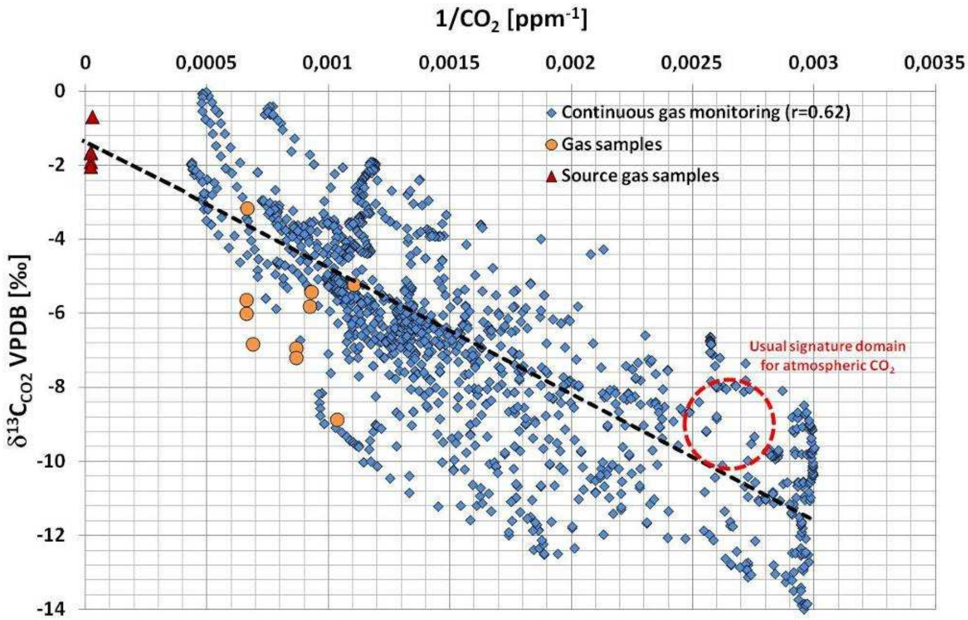

Fig. 4. Plot of carbon isotopic signature of CO_2 gas versus inverse of CO_2 gas concentration (monitored gas appears to be the result of a mixing between atmospheric gas and source gas enriched in CO_2 and having a carbon isotopic signature which is characteristic of a carbonates dissolution process)

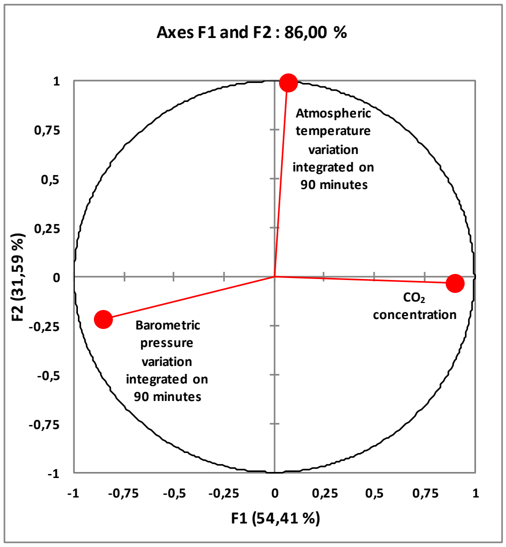

Fig. 5. Illustration of the role of barometric pressure variation as driving force for CO_2 emissions at surface (principal component analysis on about 15,000 data)

Contingency plan drawn by local authorities implied design of efficient ventilation in close spaces (e.g. cellars) where CO_2 accumulations have been detected. Filling of some identified cracks has also been performed to stop gas emissions in the most sensitive areas (e.g. cracks very close to houses, emissions with high CO_2 enrichment or O_2 depletion…).

INERIS recommends for mid/long-term remediation plans to design buildings so as they are not permeable to gas influx and by isolating first floors from cellars.

Foundations of new buildings should be gas proof to stop any penetration of gas emitted by soil. Gas tightness of old buildings should be improved by filling any potential pathway for gas (as cables and pipes passage systems or cracks in walls or floor).

Gas influx in old buildings should also be controlled by creating a pressure gradient between buildings and ground.

Feedback from this case study illustrates the fact that the vadose zone can be seen as a buffer volume which may accumulate gas migrating underground. This gas can be flushed later when meteorological conditions favor gas emissions at surface.

Because the vadose zone is the very last natural barrier before a gas leak reaches surface, it must be correctly monitored to detect any potential accumulation and prevent hazard to people. The monitoring of the vadose zone has to be taken into account when designing monitoring plans of CO_2 storages.

Since mid-2012, INERIS takes part to a new research project called “CIPRES” (Study of potential impacts of CCS on water resource) funded by the French Research Agency (ANR). INERIS is presently building a pilot site to simulate a leak of CO_2 in subsurface (fig.6). Dissolved CO_2 will be injected in a shallow aquifer at about 20 meters depth. CO_2 migration in the saturated and unsaturated zones will be monitored through observations wells. This project will aim to better characterize degassing process at water table and also dynamics of gas migration and accumulation in the vadose zone.

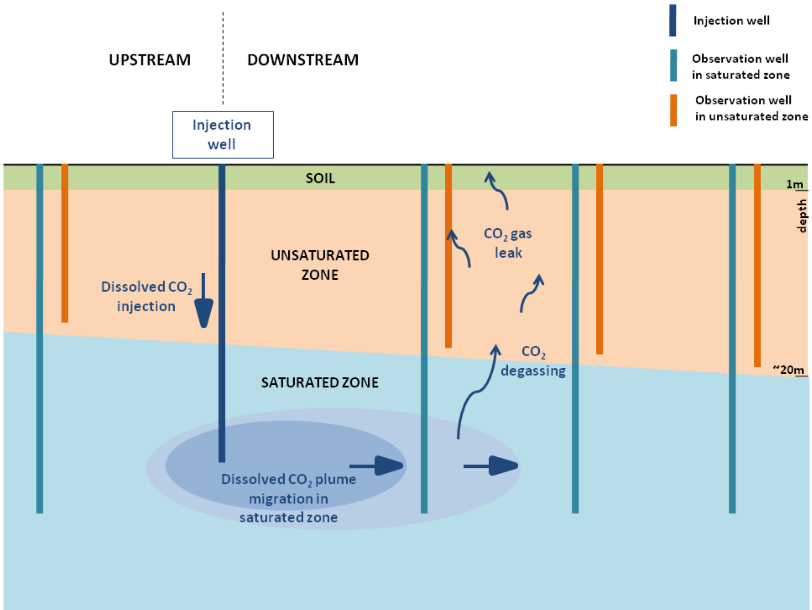

Fig. 6. Pilot site of CIPRES to study impacts of CO_2 leak on subsurface water resource and CO_2 migration and accumulation processes in vadose zone

All techniques described in table 1 have been used by INERIS several times in different contexts related to gas monitoring. All of these techniques have passed validation tests at lab, are field-deployable and ready to monitor right now CO_2 storage sites. They can be used to initially characterize storages sites during baseline studies and to monitor them during exploitation and post-exploitation phases. They can also be used to characterize anomalous gas emissions at surface (potential gas leak from the storage).

4. Conclusion

Working since 20 years on designing and testing monitoring techniques, INERIS has a range of tools ready to monitor right now CO_2 storages before injection starts (baseline studies) and during exploitation and post-exploitation phases.

In case of suspicion of a gas leak from CO_2 storage, these tools can also be helpful to draw contingency and remediation plans by characterizing:

- Gas emissions at surface to assess risks to people by crossing dangerousness of emissions with safety stakes;
- Gas migration in the subsurface to define migration process by determining what are the driving force and migration duration.

After many years of worldwide research, it's now time to answer industrial and stakeholders' expectations for efficient, field-deployable and cheap solutions to perform monitoring of storage sites. Panel of monitoring tools proposed here by INERIS can help designing surface and subsurface monitoring plans for CO_2 storage projects that are presently initiated or will be launched in a close future.

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