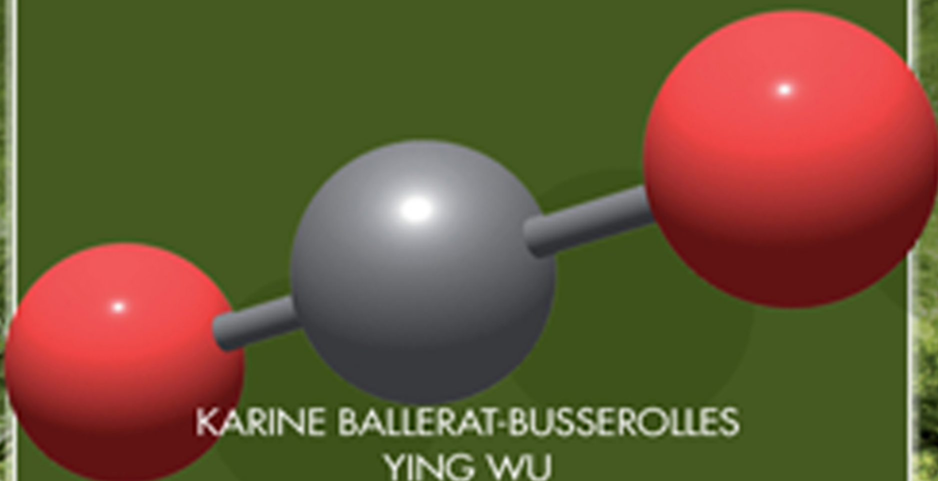
CUTTING-EDGE TECHNOLOGY FOR CARBON CAPTURE UTILIZATION AND STORAGE



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Cutting-Edge Technology for Carbon Capture, Utilization, and Storage

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Cutting-Edge Technology for Carbon Capture, Utilization, and Storage

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Preface

With the ratification of the Paris Agreement, we are now committing ourselves to achieving a temperature target of below 2°C, which represents a significant mitigation challenge. Going below 1.5 °C increases immensely this mitigation challenge. CCS has been identified as a key mitigation technology option and the IPCC 5th Assessment report showed that the least cost mitigation portfolio needs to include CCS. Unfortunately CCS has not been deployed as quickly as expected: the current global CO_2 capture and storage capacity is only 40 million tons per year, which is a tiny fraction of the 36 billion tons per year of CO_2 emitted around the globe. Nevertheless, important demonstration projects are emerging such as Boundary Dam & Quest projects in Canada and Petranova project in Texas. In Norway, three projects have also been preselected for a demonstrator to be launched in 2022.

The application of CCS to industrial sectors other than power (e.g., steel, cement, refining) is expected to deliver half of the global emissions reduction from CCS by 2050. In the near future, these industrial applications will open up, especially in Europe; there will be new opportunities and avenues for CCS that can accelerate its deployment. For these process industries, no possible alternatives for CO_2 mitigation exist that could be new energies for fossil fuels.

In North America, Enhanced Oil Recovery (EOR) is the main application considered as it allows CO_2 valorization. EOR contributes also to GHG mitigation as 40 to 50 % of the injected CO_2 remains stored. At the end of the oil production, it is also possible to continue CO_2 injection to store it in the depleted reservoirs. CO_2-EOR has been used for over 40 years, particularly in West Texas and New Mexico.

In Europe and China CO_2 EOR will also be considered but it has to be deployed, and storage in deep saline aquifers might also play an important role when a CCS business model exists, which needs to have legislation more operative, a real incentive to finance the first CCS demonstrators, and finally a CO_2 price higher than 50 €/t and not at 5 €/t as today.

CO_2 Utilization may also be considered for specific applications but it will not play an important role.

A lot of research efforts have still to be made to develop the affordable technologies allowing generalization of CO_2 capture facilities throughout the world. Amine processes have been used since 1920 in order to decarbonize natural gas but progress has to be made in reducing CO_2 capture cost, which represents 85% of the CCS final cost.

This book contains the papers presented during the CETCCUS conference which was hosted by ICCF in Clermont-Ferrand from 25th to 27th September 2017. This conference was dedicated to CO_2 Capture Utilization and Storage technologies.

We hope that it will enable as many people as possible to have a better understanding of the mechanisms involved as well as the technological and economic challenges still to be taken up to deploy CCUS technologies around the globe.

Paul Broutin
CO_2 Capture Manager
IFP Energies nouvelles
Solaize, France

Introduction

A conference with the name Cutting Edge Technology for Carbon Capture, Utilization, and Storage (CETCCUS) was held in Clermont-Ferrand, France, in September 2017. The conference attract both academic, industry, and government representatives to discuss the latest technology related to carbon capture, utilization, and storage (CCUS).

Presenters came from France, Spain, Switzerland, Italy, Denmark, the United Kingdom, Canada and China with co-authors from several other countries, showing the worldwide interest in this topic. This book is a collection of the papers presented at the conference.

The tone for the meeting was set by our keynote speaker M. Paul Broutin and his comments are briefly summarized in the preface to this volume.

Many excellent papers were presented that included new relevant experimental data, models for the data, molecular simulations, new processes for removing carbon dioxide from gas streams, and discussion of enhanced oil recovery (EOR), which is still the main method for utilization of CO_2. This book is a collection of the papers from the conference. We believe these papers shows the quality of the research in this field.

We were pleased to have had several students present at the conference. And we would like to note Ms. Marie Poulain (Chapter 9) who was awarded the ProSim Prize for Best Student Paper.

Finally, we would like to thank our sponsors: Axelera, Gas Liquids Engineering. ProSim, Swagelok, Club CO_2, Société française de physique, Société Chimique de France, The National Center for Scientific Research, Université Clermont Auvergne, Clermont-Ferrand Chemistry Institute, Auvergne Rhône Alpes Region, and The City of Clermont-Ferrand.

K.B., J.J.C., & Y.W.
September 2017

Part I

CARBON CAPTURE AND STORAGE

1

Carbon Capture Storage Monitoring ("CCSM")

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Abstract

It is a matter of fact that the manmade emission of CO_2 is contributing to global warming. In the public discussion, the CO_2 emission seems to be attributed mostly to energy generation – this is only partially true because the emissions from other industrial activities make significant contributions too.

In the light of current knowledge and technical developments the only way to reduce those emissions is to separate CO_2 and store it underground. There is no other solution – and this solution is technically possible. At least in Europe public awareness is considering CO_2 storage as a "Final Waste Material Deposit" similar to a deposit of "Nuclear Waste".

The main technical concern for such an underground storage is that no adequate monitoring method is available to permanently monitor the fluid behavior in the underground storage.

Therefore the public awareness is afraid of unexpected and uncalculated HAZARDS which may cause severe damage in the storage environment.

This paper describes a method to control the storage environment and the dynamic behavior of the fluids in storage. This method uses the omnipresent seismic background noise as a tool for monitoring the underground storage, regarded as a Technical Dynamic System.

The proposed method is based on the buildup of a "Forensic Event Space" calculating the near future of the system. The method can be used as a HAZARD assessment system for storage operations.

Keywords: permanent monitoring, Forensic Event Space

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1.1 Introduction

One of the key problems of our industrialized civilization and social economic systems is the destabilization of the biosphere by manmade emissions, which can no more be controlled and absorbed by natural processes.

Increasing emission of carbon dioxide (CO_2) has a major impact on global warning.

Significantly large quantities are created as exhaust gases from global industrial production – such as cement and steel industries, but mainly from fossil fuel driven electric power plants – but also as associated gas from oil and gas production. CO_2 has not only a negative impact on the environment as the so-called "Greenhouse Gas" – CO_2 at higher concentration is directly "lethal" for the human body.

The increase of energy consumption goes hand in hand with the increase of CO_2 emissions, and especially the decision to build more and more coal power plants is in contradiction to the overall demand to reduce CO_2 emissions.

Therefore – to reduce the emission of CO_2 into the atmosphere – the industry is aiming for a method to extract CO_2 from the exhaust gases and capture it in large quantities in artificial storages in subsurface geological formations. Such underground storages are already geologically very well known and sometimes applied as storages for natural gas in subsurface underground formations, e.g., saline aquifers. The problem with such natural storages even for temporary deposition of waste and toxic gases is to take sufficient measures to secure the stability of such storages and to avoid uncontrolled "escapes" of the captured media. The "sealing conditions" of such natural/artificial formations have to be properly investigated and determined but the most important tool to secure uncontrolled events is to install a powerful technical control and monitoring system which can help to identify hazardous and unpredicted events and predict deviations from normal operating conditions – in advance: An "Early Warning System" and "Risk Assessement System" for hazardous waste disposals.

The problem with those storages is the uncertainty of the cap rocks and the uncertainty of the geological and lithological sealing boundaries of the storage as well as the uncertainty of the inter-reactivity of different CO_2 phases with boundary spaces (Figure 1.1).

To minimize the risk of unpredictable events it is mandatory to develop methods which are able to monitor the flow and behavior of fluids inside the Carbon Capture Storage as well as lithological changes and induced boundary changes.

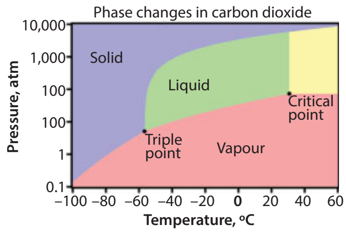

Figure 1.1 Phase Diagram CO_2. (Source: www.chemistry-blog.com).

In the public awareness, an artificial Carbon Capture Storage in subsurface geological formations is considered as "Waste Disposal of hazardous material" and consequently there is a very high degree of resistivity against such underground carbon capture storages – especially "not in my backyard". To achieve public acceptance, it is at least necessary to apply transparent monitoring technologies to reduce the uncertainty about the behavior of the technical storage conditions and the dynamics of the stored media.

Such method must be able to monitor any kind of "change of conditions" over the entire storage space and its boundaries continuously and permanently during the whole lifetime of the storage.

There is a fundamental difference – philosophically – in monitoring the fluid behavior in a tank or even in an oil reservoir – where operating parameters are monitored and measured – and monitoring the fluid behavior in an artificial storage of hazardous waste material where it is not enough to monitor the prevailing operating parameters because what actually has to be monitored is the "unpredictable" since it is assumed that something might happen beyond the operating parameters; something neither expected nor predicted. Nobody knows what will happen, or how/when/where, but everybody expects that something could happen.

1.2 State of the Art Practice

Currently in Carbon Capture Storages observation wells are drilled mainly for permanent observation purposes and they are equipped with downhole sensors to measure pressure, temperature and other physical, chemical and electrical properties of the media surrounding the borehole.

From the total data and gradients relating to all these parameters, models of the behavior of the stored media inside the storage are derived – and of course such models do not cater for the "unpredictable", which after all is the reason for monitoring and modeling.

These methods in connection with modeling techniques are very well known and very useful in application as long as the storage is a known system with stable physical and chemical properties and well defined stable boundary conditions.

A Carbon Capture Storage however represents a spatial distributed "dynamic system" with uncertain boundary conditions and the "test well monitoring concept" alone does not meet the given requirements.

The results of such monitoring methods are only reliable as long as the storage mechanism in the entire corpus behave "as modeled" but they are not able to detect phenomena beyond the models. For this reason, the classical parametric methods satisfy the control of "storage tank" working conditions but they are not suited to measure or predict the "unpredicted". Also the number of test wells is limited and so is the spatial resolution.

Another class of methods can be seen in ground penetrating radar or sonar systems but unfortunately the penetration depth and spectral properties of such methods are not suited for such applications.

A further method to identify structural and impedance changes could be seen in the application of time lapse reflection seismic (4D) – however, the penetration features and also the limited information as well as the requisite controlled source do not allow this method as a permanent and continuous monitoring tool for Carbon Capture Storages – not to mention the operation costs of such a method.

1.3 Marmot's CCSM Technology

As a solution for a permanent Carbon Capture Storage Monitoring system Marmot's CCSM provides a technical method which allows monitoring the fluid behavior inside the storage as well as structural changes using "non-invasive" technical means from the surface without penetrating mechanically into the storage space itself.

Two conditions are fundamental for such a monitoring system:

- The surveillance of the storage must be permanent and continuous and for any kind of measurement this needs a permanently and continuously operating signal source which should have no extra impact on the environment.

- The source signal must have the energetic and spectral "properties" to allow the signal to reach any "element" of the storage system in space and time – including the boundaries and sealing spaces.

The technical conclusion from these conditions is to use a broadband acoustic noise as source signal which is powerful and stable and generated by a permanent continuous source.

> **Such source signal exists in the omnipresent and omnidirectional natural seismic background – noise [1].**
>
> **The principle of analysis follows here the principles of analyzing the behavior of a technical dynamic system by pulse response or "white noise" response [18].**

The technical method is to record and analyze from the surface the spectral deformation of the seismic background and its changes in a frequency range between 0.1 and 30 Hz.

Any seismic signal can be construed as a convolution of a series of filters [2]:

$$W(t) = S_1(t) * A_2(t) * A_3(t) * A_4(t) * I_5(t)$$

where

$W(t)$ – Recorded signal
$S_1(t)$ – Undisturbed source signal
$A_2(t)$ – Filter characteristic of the storage
$A_3(t)$ – Filter characteristic of the cap rock
$A_4(t)$ – Filter characteristic of the transition zone between cap rock and surface
$I_5(t)$ – Instrument characteristic

It is a fundamental criterion for a complex "Storage System" like CCS that all geological, lithological, geophysical, geochemical and physical rock properties are very well known – otherwise it doesn't make sense to select this system and use it as a Carbon Capture Storage – as opposed to a hydrocarbon reservoir under development. And for this reason, based on the detailed knowledge of all storage properties it is possible to associate the system elements and its filter characteristics to the signal pattern components.

Marmot's CCSM technology is a spin-off of the ULF-PSSM – 5D Quantum Monitor [3] for permanent monitoring of producing oil fields and

"Time Variant Visualization of Fluid and Non-Fluid Reservoir Dynamics". This technology is based on the spectral analysis of the omnipresent and omnidirectional seismic background noise of the earth (RSSN = Random Spread Spectrum Noise).

This ULF – PSSM technology is noninvasive using the seismic background noise as source signal – it is operated with surface or near surface broadband signal converter (Resonance Spectrometer) and it delivers a broad spectrum of information from which in reservoir monitoring the following phenomena are observed and used as processing parameter:

- Frequency conversion power caused by fluid saturation parameter in porous media (non-linear transfer function for a limited frequency band)
- Stochastic resonances caused by secondary permeability fluid spaces which act as λ/4 resonators and indicate rock properties [22, 23]
- Spectral anomalies indicating complex faulting systems or/and spatial rock unconformities which transform mechanical energy into chemical energy [24]
- SLSE – Short Life Single action Events indicating spontaneous lithological changes.

The creation of side bands caused by frequency conversion at non-linear transfer elements is a well-known effect in communication instruments and electronic devices [19] but the same theory applies for acoustic wave

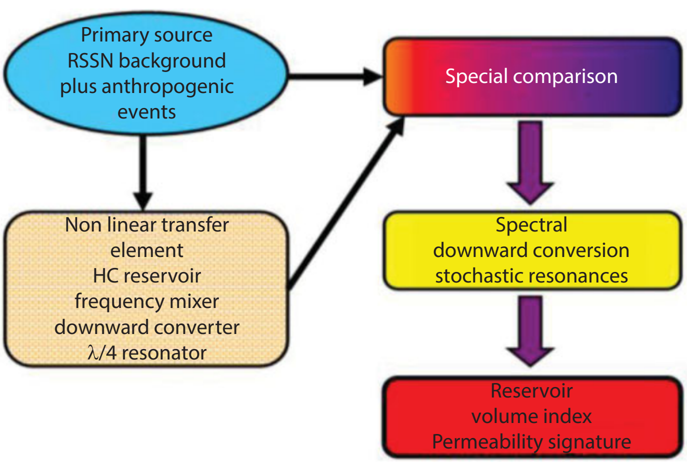

Figure 1.2 Principle of the ULF-PSSM Analysis.

propagating in anisotropic geological formations. A fluid saturated porous "body" is a frequency converter in a distinct frequency window building lower and higher sidebands from the incoming Random Spread Spectrum Noise (RSSN) of the seismic background. At the surface, these conversion products can be recorded but because of non-symmetric wave propagation in the lithosphere only the lower sidebands make a significant contribution and can be used for the calculation of fluid saturation because conversion power and fluid saturation are directly related.

The second phenomenon which contributes to the analysis of rock properties – secondary permeability – is the appearance of stochastic resonances caused by fluid prone fractures where the fluid column is acting as a λ/4 Resonator due to its geometrical and fluid properties. Each reservoir or storage has a characteristic resonator pattern depending on the rock properties (Figure 1.3).

Figure 1.3 also shows two more phenomena which are used as monitoring tools and reservoir or storage characterization. Spectral anomalies as emission or absorption spectra indicate changes in the fluid-rock system which may occur in space or even in time, when system properties are changing.

The next indicator which is very important especially in CCS monitoring is the SLSE which provides a huge amount of information including indication of micro seismic or micro tectonic events caused by micro fractures or macro fractures (in case of macro fractures we have to expect landslides, earthquakes or avalanches).

In case of a CCS system or in general a "disposal system" these events are crucial and they have to be "captured" with 100% reliability and each of these events may happen only once – only once in the whole lifetime of the storage or the system – and one of those events can be the trigger for

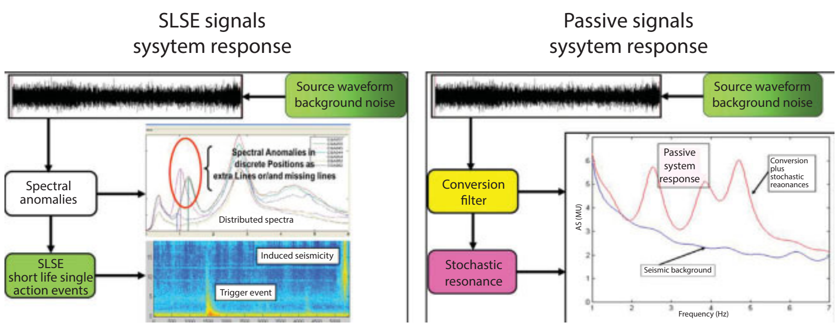

Figure 1.3 Frequency Conversion – Stochastic Resonances – Spectral Anomalies and SLSE.

the system collapse or can predict the system collapse and for this reason ***permanent monitoring*** is mandatory for system control. This is the same in oil reservoir monitoring but there the direct hazardous component is missing – the task is different.

1.4 Principles of Information Analysis

Principally we have to distinguish between signal analysis and information analysis. From the continuous signal stream information elements are separated and from those information elements an information vector

$$(x, y, z, A_1, A_2, A_3, \ldots, A_n)$$

is created. A manifold of these information vectors over time builds a so-called "event space" from which each (finite) element is attributed with a "probability"

$$\{(x, y, z, P_1, P_2, P_3, \ldots, P_n)\}(t)$$

The projection from the event space into the initial 3D cube allows the dynamic visualization of the storage "MODEL".

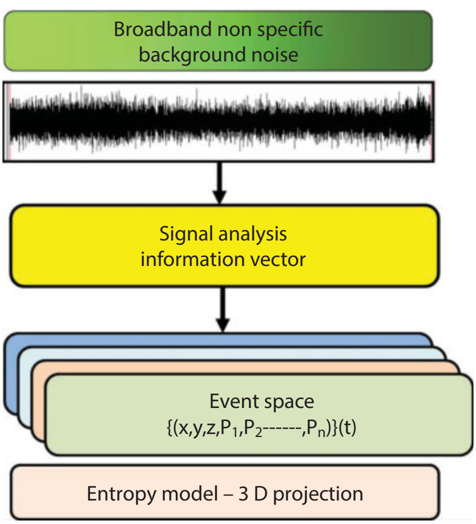

Figure 1.4 Signal – Information Flow.