Carbon Sequestration Leadership Forum
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PHASE II FINAL REPORT FROM CSLF RISK ASSESSMENT TASK FORCE

Note by the Secretariat

Background

At its meeting in November 2006 in London, the CSLF Technical Group created a Task Force to Examine Risk Assessment Standards and Procedures. This Task Force is chaired by the United States with representation from Australia, Canada, France, India, Japan, Netherlands, Norway, the United Kingdom, the United States, and the IEA Greenhouse Gas R&D Programme. A Phase I Final Report was completed in 2009, and included an overview of risk assessment and related methodologies, a review of the existing literature on risk assessment for geologic storage of CO_2, a summary of ongoing risk-assessment activities in various countries, a highlight of critical issues, and an identification of areas where additional information was needed. Phase II activities included a gap assessment to identify CCS-specific tools and methodologies that will be needed to support risk assessment, and a feasibility assessment of developing general technical guidelines for risk assessment that could be adapted to specific sites and local needs. This document is a Phase II Final Report from the Task Force.

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Phase II Report from CSLF Risk Assessment Task Force

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1. Background

At the joint meeting of the Technical and Policy Groups of the Carbon Sequestration Leadership Forum (CSLF) in London (14–15 November 2006), the CSLF Technical Group (CSLF-TG) formed a task force to examine risk assessment standards and procedures.

This task force was formed to address a need identified in the CSLF strategic plan: the development of recommendations for risk assessment standards and procedures.

In Phase I of its activities, the Risk Assessment Task Force (RATF) focused on the identification of potential risks from CCS activities and the examination of risk assessment standards and procedures that can be used to place these risks in context based on their likelihood to occur and their potential impacts.

RATF completed Phase I activities in November 2009. The Phase I Report included an overview of risk assessment and related methodologies, a review of the existing literature on risk assessment for geologic storage of CO_2, a summary of ongoing risk-assessment activities in various countries, a highlight of critical issues, and an identification of areas where additional information was needed.

1.1 Status of Recommendations from RATF's Phase I Report

The Phase I report provided a number of recommendations. The following summarizes those recommendations and any subsequent actions taken by the CSLF:

- *The link between risk assessment and liability should be recognized and considered.* This recommendation was passed to the CSLF Policy Group (CSLF-PG), which then formed a joint task force between the CSLF Policy and Technical Groups. This joint task force initiated action following the CSLF Ministerial Meeting in Beijing (2011). In July 2012, the joint task force will conduct a workshop in Paris at which a range of CCS stakeholders will help to clarify needs in the area of risk and liability.

- *Establish acceptable risk levels – Storage-integrity goals for sites should be discussed.* This recommendation was taken up in Phase II of the RATF and resulted in a white paper discussing performance goals (see Appendix II).

- *The use of risk assessment to ensure successful storage at sites should be considered in the context of stakeholder outreach and communication.* This recommendation was passed to the CSLF-PG, which, through its communication task force, developed a series of fact sheets that were vetted with the CSLF-TG and posted on the CSLF website (cslforum.org/education/index.html#inFocus; see Appendix I).

- *The CSLF-TG's Projects Interaction and Review Team (PIRT) should conduct a gap assessment to identify CCS-specific tools and methodologies that will be needed to support risk assessment.* The PIRT conducted this analysis as part of its overall gap assessment. To augment that analysis, RATF developed two additional assessments as part of its Phase II activities, both of which are summarized in this report. Section 2 presents a brief summary of potential needs/gaps in risk assessment associated with CO_2 storage in conjunction with the use of CO_2 for enhanced oil recovery (EOR). Section 3 presents a brief outline of the variation of risks associated with different phases of a project, recognizing that types and likelihoods of risks vary over the course of the project and are likely to be handled by different approaches to liability.

- *The CSLF-TG should consider the feasibility of developing general technical guidelines for risk assessment practices that could be adapted to specific sites and local needs, and subsequently development of such guidelines.* This recommendation was tabled by RATF, pending outcomes from the joint task force on risk and liability.

2. CO_2-EOR/Storage R&D Needs

The recent emphasis on CO_2 capture, utilization, and storage (CCUS) has added a new dimension to considerations related to risk assessment for CO_2 storage. This section provides a brief overview of these factors.

2.1 Integrity of Pre-Existing Wells

All EOR/storage projects will take place in reservoirs with existing wells that were required for exploration, production and/or injection of water or other fluids for secondary or even tertiary (non-CO_2) recovery. The age of these wells will vary, with some potentially being old. Consequently, completion histories for the wells will also vary. Although well work-overs are common industry practice in conjunction with CO_2-EOR, most wells developed solely in consideration of oil production needs are unlikely to have been drilled, completed and/or abandoned according to requirements specific for long-term CO_2 storage. Some oil fields, particularly in North America, may have hundreds and even thousands of wells. Both the number and condition of these wells must be considered in any assessment of storage integrity, because wellbores that penetrate the primary seal are potential pathways for leakage from the reservoir. In the future, there may also be interest in re-entering fields which are currently idle, where information on the condition of the existing wells, and, possibly even their location, may be absent. Hence, research is needed in a number of areas to mitigate the potential for CO_2 leakage through existing wells:

- Further work on methodologies to detect the presence and location of pre-existing wells.
- Development of new, more quantitative, methods to evaluate the condition (with respect to leakage) of existing wells – e.g., corrosion, cements, and in particular, characterization of the annular region between the casing and the rock.
- Development of statistical methods to characterize the condition of wells in oil fields with a very large number of wells where not every well can be individually evaluated.
- Further work on monitoring of wellbores for leakage.
- Development of improved technologies for remediating old wellbores- can “cement squeeze” technology be improved?

2.2 Optimization of EOR and Storage

Conventional CO_2 EOR production strategies, ie, well spacing, injection interval location, injection pressures, WAG strategies, etc, have been developed in order to maximize oil production while minimizing “loss” of CO_2, where “loss” refers to the CO_2 which remains underground and not reclaimed from produced oil for re-injection. In the future, if CO_2 storage affects the economics of EOR, operators may be interested in optimizing injection strategies for both production of oil and storage of CO_2 (co-optimization of oil production and CO_2 storage). While some work has already been done on this topic (e.g., Kovscek and Cakici, 2005), further research is needed to understand what variables affect this optimization, and how they might be manipulated to affect it.

2.3 Utilization of the Residual Oil Zone (ROZ)

Below what is conventionally recognized as the oil/water contact, oil may still be present, though at a saturation where it is immobile under primary production techniques. CO_2 could be used to mobilize the oil, while at the same time producing pore space for storage. Limited work to date suggests that the potential reserves of oil in ROZs, as well as the potential CO_2 storage volume, may be large. It is noted that currently available storage resource estimates do not take ROZ storage into account. Considerable research needs to be done to assess the feasibility of ROZ EOR plus CO_2 storage:

- The size of the ROZ resource, both for oil production and CO_2 storage, needs to be better defined

- Methods for site-specific characterization of the ROZ and its production and storage potential need to be developed

- Strategies for production and storage need to be developed, including laboratory studies of basic processes, numerical simulations, and field testing

2.4 Utilization of Other Oil Resources

Not all oil reservoirs are considered appropriate for conventional CO_2 EOR. In particular, CO_2 is not conventionally used for enhanced recovery operations if it is immiscible with the oil. Miscibility is a function of mainly pressure and oil properties (gravity). Though immiscible CO_2 EOR is not a new research area, it remains a challenge.

2.5 CO_2 Enhanced Gas Recovery (EGR), and Enhanced Coal Bed Methane (ECBM) and Shale Gas Recovery

In the broader context of linking CO_2 storage with value-added technologies, further research should be undertaken in all three areas related to use of CO_2 for enhanced methane recovery. Use of CO_2 to enhance recovery of natural gas from conventional petroleum reservoirs is not a conventional technology. Studies however suggest that CO_2 could be used as a displacing fluid and/or a re-pressurization fluid to enhance production of methane in conventional reservoirs. However, due to the low pressure in natural gas reservoirs at depletion, the injected CO_2 expands rapidly and mixes with the remaining gas, such that gas mixed with CO_2 would be produced. The field of enhanced gas recovery in a co-optimization scenario should be looked into. The use of CO_2 to enhance production of methane from coal has been field tested, but more research is warranted to understand the processes of CO_2 adsorption onto coal and of coal swelling. The same physicochemical processes which make CO_2 ECBM attractive should also operate in some methane-bearing organic shales, though much research remains to be done.

2.6 Other Miscellaneous Topics

None new, but further research nonetheless is needed:

- Measurement (relative permeability in particular) for fluids consisting of multiple phases and multiple components, specifically water or brine, liquid hydrocarbon (oil), and gas (including CO_2, CH_4, and potentially H_2S). Reported measurements of relative permeability for more than two phases are extremely rare, if they exist at all.

- Development and validation of reservoir simulators for the prediction of multiphase fluid flow in porous and fractured systems that account for the relative permeability measurements as discussed above.

- Development of monitoring approaches to determine phase saturations in multi-phase systems.

3. Risk-assessment considerations related to various phases of a storage project

As noted in the RATF Phase I report and in many technical studies on CO_2 storage, types and likelihoods of risks vary with different phases of a project (i.e., site-development phase, injection phase, post-injection phase, and long-term phase). Given this

Phase	Issue - Concern	Reason - Rationale
Development Phase	Identification of wells/faults/fractures	Necessary for assess containment integrity. Also identification of faults is important in predicting potential for ground motion associated with fluid injection
	Characterization of natural (background) seismicity	Background seismicity is important both for prediction of potential induced seismicity (which could impact public perception/opinion and could impact containment integrity, surface facilities, other surface structures, etc.)
	Geologic site characterization	Identification and characterization of potential receptors for consideration in risk assessment (e.g., subsurface resources, groundwater, ecosystems, and the public)
		Assess capacity/injectivity

Phase	Issue - Concern	Reason - Rationale
Injection Phase	Pressure management	Maintenance of maximum bottomhole pressures below the limit imposed by the regulatory agency; Prevention of induced seismicity Prevention of pressure effects beyond the storage complex approved by the regulatory agency Prevention of pressure effect on underground resources (water production, geothermal production, O&G, natural gas storage, …) – on water recharge capacity for open aquifers (risk of flooding)
	Plume tracking	Validate containment integrity, migration of CO_2, capacity and injectivity Verification of stored CO_2 for credits
	Brine tracking	Control displacement and migration of brine
	Leakage detection	Validate containment integrity, protection of subsurface resources, groundwater, ecosystem and the public

Phase	Issue - Concern	Reason - Rationale
Post-Injection Phase	Strategic monitoring for plume/pressure tracking	Define timeframe for monitoring period
		Validate plume stabilization and pressure recovery, ensure long term containment
		Ensure plume does not impinge on pore space not covered under deed or agreement, including other storage reservoirs
		Ensure plume does not impinge on other subsurface resources

Phase	Issue - Concern	Reason - Rationale
Long-Term Phase	Strategic monitoring	Ensure CO_2 and other potentially displaced gases (such as methane) are not released to the atmosphere Ensure groundwater protection from potential impacts associated with CO_2 or brine

Appendix I: Risk-Related InFocus Fact Sheets

CCS
inFocus Carbon Capture & Storage

CO_2 Capture — Does it Work?

THE PROCESS OF CAPTURING CARBON DIOXIDE (CO_2) FROM PLANT EMISSIONS IS ALREADY A PHYSICAL REALITY ON A SMALL SCALE. CURRENT RESEARCH EFFORTS ARE FOCUSED ON SYSTEMS FOR CAPTURING CO_2 FROM LARGE COAL-BASED POWER PLANTS, BECAUSE THEY ARE THE LARGEST STATIONARY SOURCES OF CO_2 EMISSIONS. THE ONGOING RESEARCH AND DEVELOPMENT (R&D) CHALLENGE IS CAPTURING CO_2 FROM THESE FACILITIES IN A WAY THAT IS BOTH EFFICIENT AND ALSO MAINTAINS AFFORDABLE PRICES FOR ELECTRICITY. ADDITIONALLY, R&D IS ALSO FOCUSED ON APPLYING CARBON CAPTURE AND STORAGE (CCS) TO NATURAL GAS-FIRED POWER PLANTS AND INDUSTRIAL SOURCES. ADDITIONAL RESEARCH THAT INCLUDES INTEGRATING AND SCALING UP CCS TECHNOLOGY BY BUILDING AND OPERATING COMMERCIAL-SCALE FACILITIES IN A VARIETY OF SETTINGS IS ESSENTIAL FOR MEETING R&D CHALLENGES.

OVERVIEW

CO_2 capture technology is not new or particularly unique — it has long been used by industry to remove CO_2 from gas streams where it is not wanted, or to separate CO_2 as a product gas.[1] What is novel about it in terms of the climate change debate is the research effort to integrate and optimize existing and emerging technologies for the purpose of reducing human-made atmospheric CO_2 emissions. CCS is a combination of technologies for not only capturing, but also transporting and storing CO_2 emissions from fossil fuels.

The carbon capture process has been used for several decades in the petroleum, chemical, and power industries for a variety of reasons relevant to those industrial processes.[2] Capturing all, or even just three-fourths, of the CO_2 in a typical power plant with current technology would require equipment many orders of magnitude larger — a very expensive and highly energy-intensive option.

> "New or improved technologies for CO_2 capture, combined with advanced power systems and industrial process designs, can significantly reduce the cost of CO_2 capture in the future."
>
> United Nations Intergovernmental Panel on Climate Change, Carbon Capture and Storage (2005), 344.
>
> Did You Know?

Worldwide, there are today several operational large-scale projects, along with numerous smaller facilities, demonstrating specific elements of the carbon capture process. According to the Global CCS Institute, at the end of 2010 there were 234 active or planned CCS projects globally, identified across a range of technologies, project types

[1] OECD/IEA, "Technology Roadmap: Carbon Capture and Storage," 2009, 9.

[2] National Energy Technology Laboratory, "Carbon Sequestration: FAQ Information Portal," n.d., http://www.netl.doe.gov/technologies/carbon_seq/faqs/carbon-capture.html.

and sectors. Of these, 77 are large-scale integrated projects at various stages of development. Combined, these efforts have successfully demonstrated CCS as a technically feasible CO_2 mitigation technology.[3] However, there are no fully integrated, commercial-scale power plants in operation equipped with CCS. Continued research is needed to aggressively pursue the development of low-CO_2 technologies and deploy cost-competitive CCS for both new and existing plants.

How is CO_2 captured from power plants?

Energy from fossil fuels (coal, oil, and natural gas) is released in the combustion (burning) process. The same chemical reaction that allows fossil fuels to release energy upon combustion also results in the emission of CO_2 as a by-product of the combustion process. In pulverized coal systems, which make up the vast majority of America's existing fleet of coal-based power plants, the CO_2 must be separated at fairly diluted concentrations from the balance of the combustion flue gases; in other systems, such as coal gasification, it can be more easily separated. After separation, the CO_2 is compressed to a liquid-like state (called a "supercritical fluid"), transported (usually by pipeline) to an injection well, and then pumped underground into a secure and continuously monitored geologic storage area, the final stage in the CCS process.

There are three basic types of CO_2 capture: post-combustion, pre-combustion, and oxy-combustion.

- **Post-combustion processes** separate CO_2 from combustion exhaust gases. CO_2 can be captured using a liquid solvent, such as aqueous amine solution. Once absorbed by the liquid solvent, the CO_2 is then released by heating to form a pure CO_2 stream. This technology is widely used to capture CO_2 for use in the food and beverage industry. Post-combustion capture has been carried out successfully, but so far on a relatively small scale.
- **Pre-combustion processes** convert fuel into a gaseous mixture of hydrogen and CO_2. The hydrogen is then separated and can be burned without producing any CO_2 in the exhaust gas. The remaining CO_2 can then be compressed for transport. Compared with post-combustion processes, the pressure and concentration of CO_2 in pre-combustion processes is relatively high — making separation easier to achieve and offering the potential to apply novel capture technologies, such as membranes. The fuel conversion steps required for pre-combustion are more complex than the processes involved in post-combustion. This makes the technology more difficult to apply to existing power plants. Pre-combustion capture is used in industrial processes but has not been demonstrated in much larger coal gasification concepts.
- **Oxyfuel combustion processes** use oxygen rather than air for combustion of fuel. This produces exhaust gas that is mainly water vapor and CO_2, which are easily separated to produce a pure CO_2 stream. Oxyfuel combustion systems are being developed on a small scale, in laboratory or pilot projects. This process can be applied to existing power plants.

Is CO_2 currently being captured from plants that generate electricity from coal?

No one is currently capturing CO_2 at full scale from plants that generate electricity from coal. However, there are a few CO_2 capture applications at coal-fired plants at small scale. Post-combustion separation processes (amine scrubbers) are currently used commercially in industrial coal-fueled boilers to supply CO_2 to food and beverage processors and in chemical industries, but these applications are at a scale much smaller than that needed for power-producing pulverized coal or Circulating Fluidized Bed (CFB) plants. CO_2 separation processes suitable for Integrated Gasification Combined Cycle (IGCC) plants are used commercially in the oil and gas and chemical industries at a scale close to that ultimately needed, but their application requires the addition of more processing equipment to an IGCC plant and the deployment of gas turbines that can burn nearly pure hydrogen.

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[3] World Coal Institute, "Securing the Future: Financing Carbon Capture and Storage in a Post-2012 World," November 2009, 5.

CAN CO_2 BE CAPTURED FROM ALL TYPES OF PLANTS THAT GENERATE ELECTRICITY FROM COAL?

It is technically feasible to integrate CO_2 capture technologies into all types of new coal-based power plants. However, CCS represents a significant financial investment; cost has been identified as perhaps the greatest single hurdle to CCS deployment.[4] The cost of CO_2 capture using currently available technology is very high — on the order of \$100–\$150 per tonne of CO_2 avoided for first-of-a-kind plants and \$30–\$50 per tonne of CO_2 avoided for nth-of-a-kind plants.[5] A new coal-fired plant can be designed to incorporate CCS from the very beginning, or it can be built to include upfront investments that lower the cost of later adding the technology. Retrofitting existing plants for CCS is expected to be more expensive (in terms of dollars per tonne of CO_2 avoided and the incremental impact on the levelized cost of electricity). The incremental cost of CCS varies depending on the choice of capture technology, the percentage of CO_2 captured, the type of coal used, and the distance to and from the geologic storage area. Capture technologies can also be retrofitted to existing power plants but at an even higher cost and provided that sufficient space is available for the equipment. There are also significant integration and engineering considerations that need to be addressed.

ARE THERE ANY OTHER TECHNICAL CHALLENGES?

All capture systems currently require large amounts of energy for their operation, resulting in decreased plant efficiencies and reduced net power outputs when compared to the same plants without CCS. These "penalties" mean commercially available CCS technologies would add around 80 percent to the cost of electricity for a new pulverized coal plant and around 35 percent to the cost of electricity for a new advanced gasification plant.[6] Research is aggressively pursuing ways to reduce these costs to less than a 10 percent increase in the cost of electricity for new gasification-based energy plants, and less than a 30 percent increase in the cost of electricity for traditional pulverized coal plants. In addition, research is attempting to identify "best practices" that researchers and technology users believe will allow consistently safe and effective long-term CO_2 collection, injection, and storage and provide the basis for a consistent global legal and regulatory framework.

WHERE DOES CARBON CAPTURE TECHNOLOGY GO FROM HERE?

Carbon capture has been clearly demonstrated on a small scale — the vital next step is the successful demonstration of fully integrated, large scale CCS systems on commercial-size power generating stations. There is a global need for significant financial investments to bring numerous commercial-scale demonstration projects on-line in the near future.

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[4] Bryan Hannegan, VP Environment, Electric Power Research Institute, "Future of Coal: Testimony before the U.S. Senate Committee on Energy and Natural Resources," 22 March 2007, 3, 5.

[5] Mohammed A. Al-Juaied and Adam Whitmore, "Realistic Costs of Carbon Capture," Belfer Center for Science and International Affairs, July 2009.

[6] Scott M. Klara, National Energy Technology Laboratory, "Testimony before the U.S. Senate Committee on Appropriations, Subcommittee on Energy and Water Development," 6 May 2009, 3–4, 10–11.

Interesting Facts About Carbon Capture

- One million tonnes of captured CO_2 (in a super-critical liquid state) every year would nearly fill the volume of the Empire State Building in New York City (32 million cubic feet, or 906,000 cubic meters) — source: U.S. National Energy Technology Laboratory (NETL).
- Worldwide there are 234 planned or active CCS projects, 77 of which are large integrated projects in various stages of development — source: Global CCS Institute.
- A 500 megawatt pulverized coal-fired plant produces about 10,000 tons per day of CO_2; a 1000 MW plant emits 6–8 megatonnes (one megatonne = 1 million metric tons) annually — source: Carbon Dioxide Capture and Storage, Howard Herzog, Massachusetts Institute of Technology, pages 265 and 268.
- Total global CO_2 emissions resulting from human activity are currently around 24 gigatonnes per year; the CO_2 storage capacity of hydrocarbon (coal, oil, and gas) reservoirs is estimated to be around 800 gigatonnes (one gigatonne = 1 billion tonnes). The world's deep saline formations may have a storage capacity far greater than this — source: International Energy Agency, Storing CO_2 Underground, page 10.
- Globally there are more than 8,100 CO_2 point sources (primarily fossil fuel electric power plants and industrial facilities) that could conceivably adopt CCS technologies as a means for delivering deep and sustained CO_2 emissions reductions. Collectively these facilities emit about 15 gigatonnes (gigatonne = 1 billion tonnes) of CO_2 annually — source: Global Energy Technology Strategy Program, Carbon Dioxide Capture and Geologic Storage, page 13.
- Governments and businesses need to invest as much as USD $3.4 trillion in 3,400 carbon capture projects worldwide by 2050 as just one measure to cut fossil fuel CO_2 emissions by half from 2005 levels — source: International Energy Agency.

SOURCES FOR ADDITIONAL INFORMATION

- United Nations Intergovernmental Panel on Climate Change, http://www.ipcc.ch/
- International Energy Agency, http://www.iea.org/
- World Coal Institute, http://www.worldcoal.org/
- The World Bank, http://www.worldbank.org/
- European Zero Emissions Platform, http://www.zeroemissionsplatform.eu/

OTHER INFOCUS FACTSHEETS:

- Is Geologic CO_2 Storage Safe?
- Underground CO_2 Storage: A Reality?
- Why Carbon Capture and Storage?
- CO_2 Transportation — Is it Safe and Reliable?
- 10 Facts About CCS

carbon sequestration leadership forum

Last updated September 2011

CCS
inFocus
Carbon Capture & Storage

CO_2 Transportation — Is it Safe and Reliable?

Safely and reliably transporting carbon dioxide (CO_2) from where it is captured to a storage site is an important link in the carbon capture and storage (CCS) process. CO_2 transport is already a reality, occurring on a daily basis for enhanced oil recovery (EOR), industrial, food and beverage, and other uses. But to accomplish CCS on the scale needed to reduce atmospheric greenhouse gas (GHG) buildup, CO_2 transport will have to be greatly expanded beyond what currently exists.

Overview

Once CO_2 is separated and captured as part of CCS, in most cases it must be transported to a storage area, usually a geologic reservoir. As part of this process, CO_2 is compressed to a dense state — about 150 times atmospheric pressure — to make both transportation and storage more efficient. This is called a supercritical fluid, where density resembles a liquid but with qualities that allow it to move and fill a space like gas.

This supercritical CO_2 can be transported by pipeline, truck, rail, or ship, with pipelines the most common method for transporting large quantities over long distances, such as CCS usually requires. Many experts consider CO_2 pipeline technology to be mature, stemming from its use since the 1970s for enhanced oil recovery and in other industries. Tanker and ship CO_2 transportation is very limited, and mainly found in the food and beverage industries. About 100,000 short tons (91,000 tonnes) of CO_2 are transported annually for these industries — far less than the amounts expected to be associated with a commercial-scale power plant.[1]

Pipeline construction or conversion of existing natural gas pipelines to carbon dioxide transport is under consideration globally. However, at present, nearly all existing major CO_2 pipelines are located in the United States and Canada. There are 47 high-pressure pipelines of 10 miles in length or greater in North America (see table). These pipelines total some 6,600 kilometers (4,100 miles) in length and transport 3 billion cubic feet of CO_2 daily, or 99 million tonnes (90 million short tons) annually (see "Interstate Oil and Gas Compact Commission: A Policy, Legal, and Regulatory Evaluation of the Feasibility of a National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide," December 2010, pages 14-21).

> **Achieving ambitious global CCS deployment rates over the next decade will require approximately \$15 billion to \$20 billion per year in additional investment to finance transport infrastructure and storage sites through 2020.**
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> International Energy Agency, Technology Roadmap: Carbon Capture and Storage, 24.
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> Did You Know?

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[1] World Resources Institute, "Guidelines for Carbon Dioxide Capture, Transport, and Storage," October 2008, 42–43.

inFocus: CO_2 Transportation — Is it Safe and Reliable?

The advantage of pipeline CO_2 transportation is that it can deliver a constant and steady supply, without the need for intermediate storage along a distribution route. Additionally, existing CO_2 pipelines have operated safely,[3] and have not resulted in any environmental or health and safety issues for the public. However, a greatly expanded worldwide pipeline infrastructure costing billions of dollars will need to be built within a relatively short timeframe in response to modeled policies designed to stabilize atmospheric CO_2 and avert possibly catastrophic climate change.

MAJOR NORTH AMERICAN CO_2 PIPELINES

Pipeline	Owner/Operator	Length (mi)	Length (km)	Diameter (in)	Estimated Max Flow Capacity (MMcfpd)	Estimated Max Flow Capacity (million tons/yr)	Location
Adair	Apache	15	24	4	47	1.0	TX
Anton Irish	Oxy	40	64	8	77	1.6	TX
Beaver Creek	Devon	85	137				WY
Borger, TX to Camrick, OK	Chaparral Energy	86	138	4	47	1.0	TX,OK
Bravo	Oxy Permian	218	351	20	331	7.0	NM, TX
Centerline	Kinder Morgan	113	182	16	204	4.3	TX
Central Basin	Kinder Morgan	143	230	16	204	4.3	TX
Chaparral	Chapparral Energy	23	37	6	60	1.3	OK
Choctaw (aka NEJD)	Denbury Onshore, LLC	183	294	20	331	7.0	MS, LA
Comanche Creek (currently inactive)	PetroSource	120	193	6	60	1.3	TX
Cordona Lake	XTO	7	11	6	60	1.3	TX
Cortez	Kinder Morgan	502	808	30	1117	23.6	TX
Delta	Denbury Onshore, LLC	108	174	24	538	11.4	MS, LA
Dollarhide	Chevron	23	37	8	77	1.6	TX
El Mar	Kinder Morgan	35	56	6	60	1.3	TX
Enid-Purdy (Central Oklahoma)	Merit	117	188	8	77	1.6	OK
Este I to Welch, TX	ExxonMobil, et al	40	64	14	160	3.4	TX
Este II to Salt Creek Field	ExxonMobil	45	72	12	125	2.6	TX
Ford	Kinder Morgan	12	19	4	47	1.0	TX
Free State	Denbury Onshore, LLC	86	138	20	331	7.0	MS
Green Line I	Denbury Green Pipeline, LLC	274	441	24	850	18.0	LA
Joffre Viking	Penn West Petroleum, Ltd	8	13	6	60	1.3	Alberta
Llaro	Trinity CO_2	53	85	12-8	77	1.6	NM
Lost Soldier/Werrz	Merit	29	47				WY
Mabee Lateral	Chevron	18	29	10	98	2.1	TX
McElmo Creek	Kinder Morgan	40	64	8	77	1.6	CO, UT
Means	ExxonMobil	35	56	12	125	2.6	TX
Monell	Anadarko			8	77	1.6	WY
North Ward Estes	Whitting	26	42	12	125	2.6	TX
North Cowden	Oxy Permian	8	13	8	77	1.6	TX
Pecos County	Kinder Morgan	26	42	8	77	1.6	TX
Powder River Basin CO_2 PL	Anadarko	125	201	16	204	4.3	WY
Raven Ridge	Chevron	160	257	16	204	4.3	WY, CO
Rosebud	Hess						NM

Table continued on page 3

Major North American CO_2 Pipelines (continued)

Pipeline	Owner/Operator	Length (mi)	Length (km)	Diameter (in)	Estimated Max Flow Capacity (MMcfpd)	Estimated Max Flow Capacity (million tons/yr)	Location
Sheep Mountain	Oxy Permian	408	656	24	538	11.4	TX
Shute Creek	ExxonMobil	30	48	30	1117	23.6	WY
Slaughter	Oxy Permian	35	56	12	125	2.6	TX
Sonat (reconditioned natural gas)	Denbury Onshore, LLC	50	80	18	150	3.2	MS
TransPetco	TransPetco	110	177	8	77	1.6	TX, OK
W. Texas	Trinity CO_2	60	97	12-8	77	1.6	TX, NM
Wellman	PetroSource	26	42	6	60	1.3	TX
White Frost	Core Energy, LLC	11	18	6	60	1.3	MI
Wyoming CO_2	ExxonMobil	112	180	20-16	204	4.3	WY
Canyon Reef Carriers	Kinder Morgan	139	224	16	204	4.3	TX
Dakota Gasification (Souris Valley)	Dakota Gasification	204	328	14-13	125	2.6	ND, Sask
Pikes Peak	SandRidge	40	64	8	77	1.6	TX
Val Verde	SandRidge	83	134	10	98	2.1	TX
	Totals:	4,111	6,611				

*Tabulation does not include many shorter high pressure truck lines to individual fields

Adapted from "A Policy, Legal, and Regulatory Evaluation of the Feasibility of a National Pipeline Infrastructure for the Transport and Storage of Carbon Dioxide," Interstate Oil and Gas Compact Commission, September 10, 2010, pages 20-21.

Why are pipelines considered by many experts as the best choice for CCS-related CO_2 transport?

CO_2 pipelines are an existing, safe, and efficient technology, with significant long-term operating experience in the EOR industry in the United States. While the nature and extent of a more extensive CO_2 pipeline network in the U.S. and elsewhere will depend on many factors, it is expected that early projects are likely to rely on a mix of options. These options may include not only the use of existing infrastructure, but also the development of dedicated pipelines sized and located for individual projects. Tanker ship transportation of large quantities of CO_2 may be possible for some long distance or overseas shipments; however, many human-generated carbon dioxide sources are located far from navigable waterways, meaning pipelines between sources and port terminals would still have to be built. While rail cars and trucks can also transport CO_2, these modes would be logistically impractical for large-scale CCS operations.[2]

How do we know that CO_2 pipelines will likely be safe and reliable?

Experience from decades of pipeline operations suggests that designing and operating CO_2 pipelines do not pose any new challenges. In the United States, pipeline companies have successfully operated a substantial CO_2 pipeline infrastructure for nearly 40 years, mainly for use in EOR. The oldest of these is the 225 kilometer (140-mile) Canyon Reef Carriers pipeline, which has operated since 1972 in regional Texas oil fields. The longest, the 502-mile (808 kilometers) Cortez pipeline, has been delivering about 20 million tonnes of CO_2 annually to Denver City, Texas, since 1984.[3] To date, U.S. CO_2 pipelines have experienced few incidents — 12 leaks were reported from

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[2] Ibid, 4.

[3] World Resources Institute, "Guidelines for Carbon Dioxide Capture, Transport, and Storage," October 2008, 42.

1986 through 2006, none resulting in injuries to people, making them among the safest pipeline systems used industrially.[4] Even as the number of CO_2 pipeline networks expands significantly to support CCS, existing operational experience combined with adequate risk assessment and the use of best practices is expected to result in generally safe design, construction, and operation.[5]

HOW LARGE WILL THE CO_2 PIPELINE INFRASTRUCTURE NEED TO BE FOR CCS?

The nature and extent of pipeline networks that would be necessary to transport the large quantities of CO_2 resulting from CCS will depend on many factors, including the proximity of storage sites to the capture facilities; the costs to acquire pipeline rights-of-way and associated permits; the cost to construct the pipelines; and additional costs to operate the pipelines and comply with operational and maintenance regulations. However, even in the United States where there is an existing CO_2 pipeline network that aligns relatively well with potential geologic storage areas, additional pipelines will still need to be built. A study by a Pacific Northwest National Laboratory (PNNL) team estimates the United States would need up to 23,000 miles (37,000 kilometers) of additional dedicated CO_2 pipeline between 2010 and 2050 under the 450 parts-per-million (ppm) emissions target suggested by the Intergovernmental Panel on Climate Change; this figure would drop to 11,000 miles (17,700 kilometers) under a 550 ppm scenario.[6] In the European Union (EU), where there currently are no dedicated CO_2 pipelines, one recent estimate calls for the need to transport 400 million tonnes (440 million short tons) per year by 2030 to meet EU interim targets for carbon dioxide removal.[7] To put this amount in perspective, the number of 20-ton CO_2 trucks needed to hold 400 million tonnes would circle the earth 15 times, according to one study.[8] A 2010 study by the International Energy Agency, "Global CCS Pipeline Infrastructures," estimates the cumulative transport of 1.44 gigatonnes (GT) of carbon dioxide annually from 358 sources to storage will be needed worldwide by 2030, at a cost of $60 billion. In short, any of these and other scenarios will require a large and expensive global CO_2 pipeline infrastructure.

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[4] Congressional Research Service, "Carbon Dioxide (CO_2) Pipelines for Carbon Sequestration: Emerging Policy Issues," 19 April 2007, 16.

[5] J. Barrie, K. Brown, P.R. Hatcher, H.U. Schellhase, Carbon Dioxide Pipelines: A Preliminary Review of Design and Risks, 2004, 6.

[6] J.J. Dooley, R.T. Dahowski, C.L. Davidson, "Comparing Existing Pipeline Networks with the Potential Scale of Future U.S. CO_2 Pipeline Networks," February 2009, 4–5.

[7] McKinsey & Company, "Carbon Capture and Storage: Assessing the Economics," 22 September 2008, 12.

[8] David L. Coleman, "Transport Infrastructure Rationale for Carbon Dioxide Capture and Storage in the European Union to 2050", February 2009, 1676.

inFocus: CO_2 Transportation — Is it Safe and Reliable?

What are the major challenges facing the creation of a CO_2 transportation infrastructure?

The cost of building new infrastructure could be steep, especially for countries or areas lacking adequate geologic storage sites. Consequently, governments may need to provide financial incentives that reduce costs for pipeline developers and operators. Aside from costs, there are also additional challenges, including pipeline network requirements, economic regulation, siting, regulatory classification of CO_2 itself, safety and health issues, and liability. Pipeline transport of CO_2 through populated areas will require that special attention be paid to design factors, overpressure protection, and leak detection. However, there is no indication that potential problems for CO_2 pipelines are any more challenging than those faced by hydrocarbon pipelines in similar areas (such as natural gas and petroleum), or that they cannot be resolved. In the final analysis, a balance must be struck between the need to protect people and the environment, and the impending requirement to rapidly deploy CCS to help mitigate the effects of climate change. Progress will be accelerated by countries working together to develop common regulatory and infrastructure approaches.

Sources for Additional Information

- United Nations Intergovernmental Panel on Climate Change, http://www.ipcc.ch/
- International Energy Agency, http://www.iea.org/
- World Coal Institute, http://www.worldcoal.org/
- The World Bank, http://www.worldbank.org/
- European Zero Emissions Platform, http://www.zeroemissionsplatform.eu/

Other inFocus Factsheets:

- Is Geologic CO_2 Storage Safe?
- Underground CO_2 Storage: A Reality?
- Why Carbon Capture and Storage?
- CO_2 Capture: Does it Work?
- 10 Facts About CCS

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Underground CO_2 Storage: A Reality?

Capturing and storing carbon dioxide (CO_2) underground is not a new or emerging technology — it is already a reality on a small scale. There are large carbon dioxide storage reservoirs throughout the world that experts believe can accommodate centuries worth of injected CO_2. Additionally, the various technical components of carbon capture and storage (CCS) have been separately proven. But using the technology on the commercial scale necessary to impact global climate change remains prohibitively expensive. Continued research is needed to lower costs of the technology itself and confirm all aspects of geologic storage, including reservoir size, safety, and reliability.

OVERVIEW

There are decades of operational experience from CCS projects, including underground CO_2 injection for enhanced oil recovery (EOR) and the use of technologies analogous to carbon capture and storage, such as acid gas injection and natural gas storage. Three large-scale storage projects — injecting 1 million to 2 million tonnes of CO_2 annually — have been operating for several years, and five smaller projects are now actively capturing and storing carbon dioxide. There are also capture-only projects for industrial use. These industrial-level experiences are complemented by numerous research-scale CCS projects, intergovernmental and industry partnerships, research programs, and stakeholder networks. No adverse safety, health, or environmental effects have ever resulted from any of these operations.

Scientists believe the earth has extensive capacity for storing injected carbon dioxide. The United Nations Intergovernmental Panel on Climate Change (IPCC) estimates the world's potential capacity at 2 trillion tonnes, although there could be a "much larger potential."[1] The bottom line is that many pieces of the CCS puzzle have been deployed and verified separately but no commercial-scale power plants using the technology have yet been constructed. This is an essential step before CCS can be deployed commercially. Meanwhile, existing projects and research initiatives are helping researchers and operators acquire the real-world experience and data needed to advance the technologies, lower costs, and validate CCS potential and storage capabilities.

In the United States, CO_2 has been injected underground for enhanced oil recovery operations for decades; about 63 million tonnes of mostly naturally produced CO_2 are injected annually for this purpose.

U.S. Department of Energy, National Energy Technology Laboratory, "The Role of Underground CO_2 Accumulations in the Emergence of CO_2 Enhanced Oil Recovery," June 2011, Executive Summary, 1.

Did You Know?

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[1] U.N. IPCC, "Special Report on Carbon Dioxide Capture and Storage: Summary for Policymakers," 2005, 12.

inFocus: Underground CO_2 Storage: A Reality?

WHAT IS A GEOLOGIC FORMATION AND HOW DOES IT SEQUESTER CO_2?

The concept involves storing CO_2 deep underground (typically at depths greater than 800 meters, or more than 2,600 feet) in geologic formations[2] with characteristics that would trap large volumes of CO_2 and not allow it to leak. Some of these characteristics include tiny microscopic spaces generally filled with salty water, known as **porosity**; sufficient connection between the open spaces so that CO_2 can flow sideways or move around within the formation, known as **permeability**; and a confining layer that can "**cap**" the upward flow so that CO_2 is trapped underground.

Many types of geologic formations have these features, such as sandstones and limestones, and some geologic formations are tens to hundreds of feet thick and may extend laterally for miles.

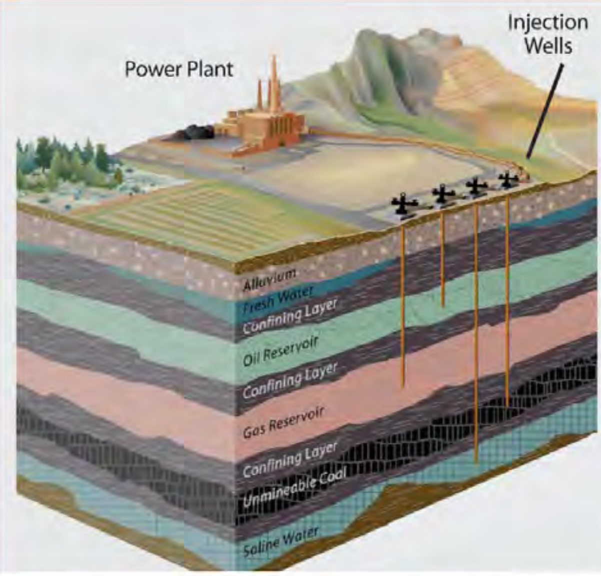
Geologic formations that are potential CO_2 reservoirs are the same as reservoirs that trap oil and gas and naturally occurring CO_2. Oil and gas can be found in sandstones, limestones, and other permeable formations, trapped for millions of years until tapped by wells drilled from the surface to extract the oil.

An overlying layer of low permeability rock, commonly referred to as a **caprock** or geologic seal (such as shales or siltstones), prevents oil and gas from traveling out of the permeable formation. Similarly, a caprock or geologic seal would be expected to trap CO_2 and prevent it from migrating upwards.

HOW IS CO_2 INJECTED UNDERGROUND AND WHY DOES IT STAY THERE?

CO_2 is compressed into a dense fluid then pumped — via one or more wells — into a porous geological formation. At first, being more buoyant than water, the CO_2 rises to the top of the formation, where it becomes trapped beneath a confining layer of impermeable caprock (see description above) which acts as a seal: Caprocks have trapped oil, gas, and CO_2 underground for millions of years.

However, it is not long before other trapping mechanisms also start to take effect: during injection, and as the CO_2 shifts within the formation, some of it becomes trapped in the tiny pore spaces of the rocks and does not move. The CO_2 also starts dissolving into the saline formation (the way sugar dissolves in hot tea) and being heavier than the water around it, the carbonated water sinks to the bottom of the formation, trapping it indefinitely. Finally, the dissolved CO_2 reacts chemically with the rocks to produce minerals, much like shellfish use calcium and carbon from seawater to form their shells. Depending on the chemistry of the rocks and water, this process can be very rapid or very slow, but it effectively binds the CO_2 to the rocks.



Schematic illustrating the process of carbon capture and storage (also known as sequestration). Adapted from Energy and Geosciences Institute, The University of Utah illustration.

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[2] To classify and map layers of rock, geologists created a basic unit called a formation. A formation is a rock unit that is distinctive enough in appearance that a geologic mapper can tell it apart from the surrounding rock layers. It must also be thick enough and extensive enough to plot on a map.

carbon sequestration leadership forum

WHY ARE SCIENTISTS SO OPTIMISTIC THAT GEOLOGIC CO_2 STORAGE WILL WORK?

No emissions control technology, including carbon capture and storage, is risk-free. But several projects are already successfully storing millions of tonnes of CO_2 underground. To date, five large-scale CO_2 storage projects (greater than 1 million tonnes of CO_2 per year — enough to fill the Empire State Building — over the storage period) are underway worldwide — two in Norway, and one each in Algeria, Canada, and the United States.

The Sleipner Project, located approximately 150 miles (241 kilometers) off the coast of Norway in the North Sea is storing more than 2,700 tonnes of CO_2 per day, injected 2,600 feet (792 meters) below the seabed. Over the lifetime of the project, more than 20 million tonnes of CO_2 are expected to be injected into the saline formation, which is sealed at the top by an extensive and thick shale layer. Monitoring surveys of the injected CO_2 indicate that over the past 13 years, the gas has spread out over nearly two square miles underground without moving upwards or out of the storage reservoir. Long-term simulations also suggest that over hundreds to thousands of years the CO_2 will eventually dissolve in the saline water, becoming heavier and less likely to migrate away from the reservoir.

Additionally, oil and natural gas companies have more than 40 years of experience storing natural gas deep underground and using injected CO_2 to "push" oil toward producing wells (i.e., EOR). According to the International Energy Agency (IEA), the success of these projects, as well as the increasing number of research demonstrations, provides "growing confidence in the potential to store large quantities of CO_2 underground — safely and securely."[3]

The IPCC notes:

> **"Information and experience gained from the injection and/or storage of CO_2 from a large number of existing enhanced oil recovery (EOR) and acid gas projects, as well as from the Sleipner, Weyburn, and In Salah projects, indicate that it is feasible to store CO_2 in geological formations as a CO_2 mitigation option. Industrial analogues, including underground natural gas storage projects around the world and acid gas injection projects, provide additional indications that CO_2 can be safely injected and stored at well-characterized and properly managed sites."[4]**

Globally, there are currently more than 8,100 large CO_2 point sources (accounting for more than 60 percent of all anthropogenic CO_2 emissions) that could conceivably adopt CCS technologies as a means for delivering deep and sustained CO_2 emissions reductions.

"Carbon Dioxide Capture and Geologic Storage," Global Energy Technology Strategy Program, April 2006, 8.

Did You Know?

WHERE WOULD LARGE AMOUNTS OF CO_2 LIKELY BE STORED?

The IPCC has identified prospective areas in sedimentary basins (see map) where saline formations, or oil, gas, and coal fields potentially suitable for CO_2 storage are located.[5] These formations are widely distributed around the world and many are near large groupings of power plants and other industrial facilities.

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[3] IEA Greenhouse Gas R&D Programme, "Storing CO_2 Underground," 2007, 2.

[4] U.N. IPCC, "Special Report on Carbon Dioxide Capture and Storage," 2005, 197.

[5] U.N. IPCC, "Special Report on Carbon Capture and Storage: Summary for Policymakers," 2005, 9.

inFocus: Underground CO_2 Storage: A Reality?

ROCKS IN DEEP SEDIMENTARY BASINS ARE SUITABLE FOR CO_2 STORAGE

IPCC, "Special Report on Carbon Capture and Storage," 2005, Figure 5.14. "Distribution of Sedimentary Basins Around the World," 214.

Depleted oil and gas fields, deep saline formations, and unmineable coal seams have been suggested as favorable CO_2 geological storage sites. Here, various physical (e.g., highly impermeable caprock) and geochemical trapping mechanisms would prevent the CO_2 from escaping to the surface. In the future, companies may be able to inject CO_2 into coal seams and produce natural gas from the seams as an added benefit.

Saline formations contain highly mineralized brines (or very salty water) that are unsuitable for agriculture or human consumption. Saline formations have been used for storage of chemical waste in a few cases. The main advantages of saline formations are their large potential storage volume and their common occurrence. Other possibilities include deep basalt formations and shales.

HOW MUCH CO_2 CAN BE STORED UNDERGROUND?

As scientists work to refine methodologies, estimates of global geologic storage capacity can be highly variable. Nevertheless, numerous studies suggest there is extensive worldwide potential for permanently storing large quantities of CO_2 in geological formations.

As previously noted, the IPCC has identified a technical potential of at least 2 trillion tonnes of worldwide CO_2 storage capacity in geological formations and they also note: "There could be a much larger potential for geological storage in saline formations, but the upper limit estimates are uncertain due to lack of information and an agreed methodology."[6]

A more recent report prepared by the United States Department of Energy (DOE) has documented between 1.85 trillion and 20.5 trillion tonnes of CO_2 storage potential in oil and gas reservoirs, coal seams, and saline formations across the United States and Canada. Preliminary estimates suggest the availability of centuries worth of CO_2 storage for the United States and Canada in these geologic formations.[7]

A preliminary estimate by scientists at DOE's Pacific Northwest National Laboratory (PNNL) indicates there is nearly 11 trillion tonnes of potential global deep geologic storage capacity, "which, assuming other advanced energy technologies (such as nuclear and renewables) are developed and deployed along with CCS, should be more than enough to address global CO_2 storage needs for this century."[8]

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[6] U.N. IPCC, "Special Report on Carbon Dioxide Capture and Storage: Summary for Policymakers," 2005, 12.

[7] National Energy Technology Laboratory, "Carbon Sequestration Atlas of the United States and Canada — Third Edition, 2010, page 155.

[8] James Dooley, Robert Dahowski, and Casie Davidson, Pacific Northwest National Laboratory, "CCS: A Key to Addressing Climate Change," Chapter 4 in "Fundamentals of the Global Oil and Gas Industry," 2007, vol. 2007, 67–69.

In Europe, the EU project GESTCO estimated the CO_2 storage capacity in oil and gas fields in and around the North Sea at 37 billion tonnes, which would enable this region to inject CO_2 for several decades once the fields are depleted.[9]

One report notes: "In a world in which there is a broad portfolio of complementary carbon management technologies that can be drawn upon (e.g., energy efficiencies, renewable energy, nuclear power, etc.), it would appear that the deployment of CCS systems will not be constrained by a lack of overall storage capacity."[10] Meanwhile, as part of ongoing research, the Carbon Sequestration Leadership Forum (CSLF) is seeking to develop a clear set of definitions and methodologies to allow scientists to provide consistent assessments of worldwide CO_2 storage capacity.

It Seems Like Geologic Storage is Pretty Promising. Why is More Research Needed?

There is scientific consensus that CO_2 storage in deep underground geologic reservoirs has great potential as one of several climate change mitigation strategies. But there are substantial financial, institutional, regulatory, and technical challenges that need to be overcome before CCS can be widely deployed. One of these involves completing the database necessary to assure we can safely and effectively store the large volumes of CO_2 necessary to achieve significant emissions reductions from fossil-fuel power plants. Rapid progress is being made in this area, but continued field tests to fully characterize geologic storage sites, validate models and prior findings, and develop measurement, monitoring, and verification (MMV) instrumentation is essential.

> "Observations from engineered and natural analogues as well as models suggest that the fraction (of stored CO_2) retained in appropriately selected and managed geological reservoirs is very likely to exceed 99 percent over 100 years and is likely to exceed 99 percent over 1,000 years."
>
> IPCC, Special Report on Carbon Dioxide Capture and Storage, "Summary for Policymakers," 2005, 14.
>
> **Did You Know?**

Sources for Additional Information

- United Nations Intergovernmental Panel on Climate Change, http://www.ipcc.ch/
- International Energy Agency, http://www.iea.org/
- World Coal Institute, http://www.worldcoal.org/
- The World Bank, http://www.worldbank.org/
- European Zero Emissions Platform, http://www.zeroemissionsplatform.eu/

Other inFocus Factsheets:

- Is Geologic CO_2 Storage Safe?
- Why Carbon Capture and Storage?
- CO_2 Capture — Does it Work?
- CO_2 Transportation — Is it Safe and Reliable?
- 10 Facts About CCS

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[9] European Union Fifth Framework Programme for Research and Development, "Geological Storage of CO_2 from Combustion of Fossil Fuels," November 2004, 9.

[10] Global Energy Strategy Technology Program, "Carbon Dioxide Capture and Geologic Storage," April 2006, 8.

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Is Geologic CO_2 Storage Safe?

There is scientific consensus, and growing evidence, that geologic storage has great potential for safely and permanently storing carbon dioxide (CO_2). Additional research is underway to acquire the data needed to completely validate CO_2 storage potential, capability, reliability, and safety.

Overview

The idea of injecting large quantities of CO_2 underground and having it stay there without leaking or causing environmental harm is a concern for some people unfamiliar with carbon capture and storage (CCS) technology. But there is a growing body of evidence that geologic storage is both safe and effective. Ongoing global research is helping scientists accumulate information needed to conclusively verify all operational and safety aspects of long-term CO_2 storage in depleted or declining oil and natural gas fields, saline reservoirs, unmineable coal seams, and other significant geologic formations. The goal is to scientifically confirm storage safety across the diversity and composition of storage sites, both necessary predecessors of large-scale commercial CCS deployment. CCS is widely considered a key component of a portfolio response strategy (including renewable and nuclear energy, and increased energy efficiencies) necessary for meeting ambitious worldwide atmospheric CO_2 reduction goals.

> "The reason CO_2 storage works is simple: it uses the same natural trapping mechanisms which have already kept huge volumes of oil, gas, and carbon dioxide underground for millions of years."
>
> European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP)
>
> Did You Know?

Can CO_2 be securely stored in deep underground geologic formations?

Evidence, both natural and human-generated, strongly suggests the answer is a definitive "yes." The United Nations Intergovernmental Panel on Climate Change (IPCC) notes there are many natural geologic deposits of CO_2 trapped in rock formations underground: "**Underground accumulation of carbon dioxide (CO_2) is a widespread geological phenomenon, with natural trapping of CO_2 in underground reservoirs.**"[1] Natural trapping mechanisms, including pressure and physical and chemical characteristics of rock and geologic formations, have kept large volumes of not only CO_2, but also oil and natural gas deep underground for millions of years.

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[1] United Nations Intergovernmental Panel on Climate Change (U.N. IPCC), "Special Report on Carbon Dioxide Capture and Storage: Chapter 5, Underground Geologic Storage," 2005, 5-4.

Additionally, the oil and gas industry has used CO_2 injection and storage for more than 40 years to recover oil from depleted or declining fields (known as "Enhanced Oil Recovery," or EOR). Currently in the United States (which accounts for 94 percent of worldwide CO_2-EOR oil production), more than 48 million tonnes (or 52.8 million short tons) per year of CO_2 are used for this purpose.[2]

Finally, there is the experience gained from demonstration projects around the world.

Eight Projects Actively Capturing and Storing CO_2

Project Name	Location	Started Storage (Year)	Tonnes Stored Annually*
Sleipner EOR	Norway	1996	1.0
Weyburn-Midale EOR	Canada	2000	2.7–3.2
In Salah Gas Storage EOR	Algeria	2004	1.2
Crust K12-B Test	Netherlands	2004	0.2
Zama (EOR)	Canada	2005	0.067
Snøhvit Field LNG and CO_2 Storage	Norway	2008	0.75
SECARB Cranfield EOR	United States	2009	1.0–1.5
Mountaineer CCS	United States	2009	0.1

* Million Tonnes

As of 2010, the three longest operating projects — Sleipner, Weyburn-Midale, and In Salah — had a cumulative total of 11 million, 18 million, and 3 million tonnes of CO_2 stored, respectively.

Three large-scale projects — Sleipner, Weyburn, and In Salah — have been injecting and successfully storing 1 million to 3 million tonnes of CO_2 annually for several years; five others have more recently begun operations; no adverse safety, health or environmental effects have resulted from any of these projects. Through these and other projects that are operating or will be soon, scientists are acquiring the data needed to completely validate the capacity and potential impact of geologic CCS. Continuing this research is vital to deploying the technology on a commercial basis. Based on the success encountered thus far, experts believe good site selection and characterization, proper CO_2 injection rates, appropriate monitoring, and safe operational and remedial practices will assure the long-term viability of CCS technology.

But what happens if a CO_2 leak occurs?

Potential geologic storage sites will need to be carefully selected and managed so as to minimize any chance of CO_2 leakage. Given the complexity of most geologic reservoirs and the potentially huge volumes of CO_2 that may be injected, the possibility of some leakage over time may never be completely eliminated. But scientists expect the reservoir characterization process (using geologic and engineering data to quantify a potential storage area's characteristics) will rule out geologic formations that do not have adequate caprocks or other geologic seals, are intersected by faults or fractures that might be pathways for escaping CO_2, or are in areas prone to earthquake or volcanic activity. Additionally, measuring, monitoring, and verification programs will be used to plot the migration of injected CO_2 over time to detect potential reservoir leakage.

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[2] National Energy Technology Laboratory, "Carbon Sequestration Through Enhanced Oil Recovery," http://www.netl.doe.gov/publications/factsheets/program/Prog053.pdf, April 2008, 2.

The geological formations that would be used to store CO_2 are porous rock (not open underground caverns), making massive releases extremely unlikely. In fact, because the CO_2 becomes trapped in the tiny pores of rocks, any leakage through the geological layers would be extremely slow, allowing plenty of time for it to be detected and dealt with. Any such leak would not raise local CO_2 concentrations much above normal atmospheric levels.[3]

Higher concentration leaks could come from man-made wells and are likely to diffuse quickly. In addition, the oil and gas industry already has 50 years of experience in monitoring wells and keeping them secure. Storage sites will not, of course, be located in volcanic areas.

Should movement of CO_2 from the storage reservoir occur during or after injection, methods are generally available to fix the leak. Most of these methods have long been used to fix leaks from other types of wells (used for natural gas storage and liquid waste disposal). These techniques can also be used for CO_2, with the advantage that unlike those other materials, CO_2 is not explosive, flammable, or toxic. It is reasonable to expect that these techniques would work for CO_2. Because it has not been necessary to fix leaks at existing geologic storage projects, they have not yet been used for this purpose.

> "... evidence from natural systems demonstrates that reservoir seals exist that are able to confine CO_2 for millions of years and longer."
>
> United Nations Intergovernmental Panel on Climate Change, "Special Report on Carbon Dioxide Capture and Storage," 5-61.
>
> **Did You Know?**

CAN STORED CO_2 EXPLODE?

CO_2 does not burn or explode; in fact, it is a flame retardant commonly used in extinguishers. CO_2 is only problematic at very high concentrations in closed settings.

Although it is a major greenhouse gas, CO_2 is also a fundamental and essential part of nature. Plants need it to grow, while animals and humans exhale it. It also leaks naturally from volcanoes and geysers.

CAN INJECTING CO_2 UNDERGROUND CAUSE EARTHQUAKES?

CO_2 storage operations are designed to avoid inducing earthquakes. A detailed survey takes place to identify any potential leakage pathways (including seismic faults) before a CO_2 storage site is selected — if these are discovered, then the site will not be selected for CO_2 injection.

During injection, scientists and engineers can ensure that the pressure of the CO_2 does not exceed the strength of the rock by limiting injection rates and volumes, thereby avoiding over-pressurization of the reservoir.

Additionally, CO_2 storage sites have demonstrated the ability to retain injected carbon dioxide even if a natural earthquake occurs nearby. In October 2004, a major earthquake measuring 6.8 on the Richter scale occurred 12 miles from the injection site of a CO_2 geologic storage site at Nagaoka, Japan. This project stored CO_2 in a saline formation nearly a mile deep. Injection activities were halted immediately after the earthquake, but were resumed shortly thereafter. The storage formation was monitored before, during, and after the earthquake and no leakage has ever been detected.[4] Further evidence that earthquakes would not cause leaks is that a large number of producing oil and gas fields in California are near seismically active faults. They have virtually the same trapping mechanisms as CCS and earthquakes over many years have not caused them to leak.

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[3] European Technology Platform for Zero Emission Fossil Fuel Power Plants, "Frequently Asked Questions," n.d., http://www.zeroemissionsplatform.eu/faq.html/carbon-dioxide-capture-and-storage.

[4] Hiroshi Yamagata, Japan Ministry of Economy, Trade, and Industry, "Carbon Capture and Storage Activities in Japan," n.d., http://www.cslforum.org/publications/documents/Japan_CCS.pdf, 4.

CAN GEOLOGIC CO_2 STORAGE CAUSE GROUNDWATER CONTAMINATION?

To date, no known contamination of groundwater has occurred from the capture and geologic storage of CO_2.[5] Storage sites must be properly selected/designed, fully characterized, and appropriately monitored. If a site was to be improperly characterized or designed and leakage occurred that was not subsequently controlled, then CO_2 could migrate toward the surface.

CO_2 injection will be much deeper (more than a mile underground) than usable sources of groundwater and will generally be contained by one or more layers of thick, impermeable caprock.

CO_2 injection is proposed for deep saline formations containing water, but this water is unusable because of its high salt and mineral content. Given proper site selection and operation, the risks to usable water supplies would be extremely small. In the unlikely event that CO_2 would migrate upward toward shallower groundwater, seismic monitoring, groundwater analysis, and chemical tracers can detect any CO_2 that migrates upward into groundwater reservoirs and evaluate its effect on water quality.

WHAT IS AT RISK IF CO_2 LEAKS?

CO_2 is not toxic, flammable, or explosive (like methane or propane gas, for example), but if allowed to accumulate in enclosed spaces at high concentrations, CO_2 could displace oxygen and cause unconsciousness or asphyxiation. The chances of such high concentrations forming during CO_2 injection for carbon storage are remote, assuming the reservoir is well characterized.

The effects of CO_2 on terrestrial ecosystems are well known as there are many places worldwide where CO_2 seeps naturally to the surface before harmlessly dispersing in the air. We also know that soils commonly contain high concentrations of natural CO_2 produced by the respiration of soil organisms and many soil animals are tolerant of CO_2 levels in the 10–15 percent range. The effects on other animals and humans are also well known — man has been living in high CO_2 flux areas (e.g., near volcanoes) since prehistoric times.

> **"On the surface, air and soil sampling can be used to detect potential CO_2 leakage while changes deep underground can be monitored by detecting sound (seismic), electromagnetic, gravity, or density changes within the rock formations."**
>
> World Coal Institute, "IEA Greenhouse Gas R&D Programme," 4.
>
> Did You Know?

HOW WOULD LEAKS BE DETECTED?

Before a CO_2 storage site is chosen, a detailed survey takes place to identify any potential leakage pathways and assess the storage integrity of the site. Only sites with a high level of integrity are selected for CO_2 storage. In the United States, Europe, and other parts of the world, underground gas storage (natural gas and hydrogen) has an excellent safety record, with sophisticated monitoring techniques that are easily adaptable to CCS.

Surface air and soil sampling can be used to detect potential CO_2 leakage, while underground changes can be monitored by detecting sound, electromagnetic, gravity, or density changes (see World Coal Institute reference in box above).

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[5] Sally M. Benson, "Carbon Dioxide Capture and Storage: Assessment of Risks from Storage of Carbon Dioxide in Deep Underground Geological Formations," 2 April 2006, 22.

The risk of leakage through man-made wells is expected to be minimal because they can easily be monitored and fixed, and closed, if necessary.

SOURCES FOR ADDITIONAL INFORMATION

- United Nations Intergovernmental Panel on Climate Change, http://www.ipcc.ch/
- International Energy Agency, http://www.iea.org/
- World Coal Institute, http://www.worldcoal.org/
- The World Bank, http://www.worldbank.org/
- European Zero Emissions Platform, http://www.zeroemissionsplatform.eu/

OTHER INFOCUS FACTSHEETS:

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Appendix II: White Paper on Performance Based Standards

Performance based standards for site safety and integrity

The CSLF Technical Group, during the meeting of 1-2 April, 2009, noted that the Policy Group required specifying ins and outs raised by four of the recommendations resulting from the 3rd workshop on Near-Term Opportunities for CCS.

Among these four recommendations, the Technical Group decided that the recommendation n°14 " Governments working with stakeholders need to develop performance-based standards for storage site safety and integrity ", required specific work to produce a document which could review the state of the art on this question, and could identify the principal gaps to be addressed in this area.

This work was assigned to a specific Working Group. France proposed to lead it and the following countries volunteered to contribute:

- Canada (S. Bachu)
- France (O. Bouc, L. de Lary de Latour, D. Bonijoly, H. Fabriol)
- Japan (M. Akai)
- Netherland (H. Schreurs)
- SA (F. Goede)
- USA (G. Guthrie)

At a subsequent Technical Group meeting in March 2010 it was proposed and agreed that this Working Group should merge into the Task Force on Risk Assessment.

Introduction

The reduction of Greenhouse Gas emissions is an objective shared by many countries in order to limit the harmful effects of climate change. International agreements tend to quantify these objectives of reduction, and in parallel, to propose technical solutions making it possible to achieve these goals.

Among the proposed technical solutions, the CO_2 Capture, transport and Storage (CCS) in the geological media, addresses the need for urgency for action and for volumes of emissions to be reduced, while guaranteeing the access to energy which will remain, for the decades to come, based on the use of fossil fuels.

Although geological storage of CO_2 seems a reliable and secure solution in the short term, thanks to the experience acquired in the field of geological storage of natural gas and through all the operations of pumping and/or injection of various fluids in the underground (oil industry: EOR, acid gas injection), this technical solution raises the particular question of long-term safety, because of the requirement for long term retention (several hundreds to a thousand of years). Thus, it is necessary to demonstrate that, for long periods of time, the stored gas is located in the place where it was permitted to be through the regulatory process of application and permitting, and that, in the case of abnormal events which would lead this gas to move towards the surface, the risk it would present with respect to the environment and to humans, would be sufficiently negligible to be acceptable. This is why all stakeholders (operators, governments and the public) are asking for clear and transparent performance criteria, to make it possible to guarantee the safety and integrity of CO_2 storage.

This document provides a progress report on the state of the art in this field as of 2010.

First, it presents a review of the technical requirements necessary for the establishment of performance and safety standards.

Second, it reports the current various regulatory approaches to be used possibly to guarantee the safety and integrity of storage sites on the basis of the technical criteria described previously.

In the end, it identifies the main knowledge gaps which need to be covered in order to make this technology acceptable to the various stakeholders.

In the following, “performance” of a storage site is referred to as its ability to contain CO_2 underground long enough to make a valuable contribution to the mitigation of global change, *i.e.* to achieve the purpose it was designed for. This notion is distinct from storage safety, which refers to the absence of significant adverse effects to humans and the environment resulting from this activity.

Technical requirements for performance-based standards for storage site safety and integrity

Which performance objective for a CO_2 storage site?

A review of the literature dedicated to CO_2 storage risk assessment reveals a high variability in the time frames suggested for CO_2 retention in the subsurface, usually ranging from 100 years to 10,000 years. However, since the publication of the IPCC Special Report on CCS (IPCC, 2005), the value of 1,000 years seems to become more widely adopted. The required duration of effective CO_2 storage to mitigate climate change is highly uncertain, due to limited knowledge of the magnitude of CCS implementation and the relative importance of stored CO_2 compared to future emissions, of the kinetics of climate response to CO_2 storage, and more broadly to uncertainties inherent in future climate evolution scenarios (dependent in particular on the availability and cost of fossil fuels and on future energy policies).

In its Special Report on CCS, the IPCC (2005) suggested a number of elements to address this question:

- From a technical point of view, the authors stated that “for large-scale operational CO_2 storage projects, assuming that sites are well selected, designed, operated and appropriately monitored”:
  - It is “very likely” (*i.e.* with “a probability of 90 to 99%”) that “the fraction of stored CO_2 retained is more than 99% over the first 100 years”, which corresponds to a mean annual release[1] rate of 10^{-4} of the amount stored;
  - It is “likely” (*i.e.* with “a probability of 66 to 90%”) that this fraction “is more than 99% over the first 1000 years”, which corresponds to a mean annual release rate of 10^{-5} of the amount stored.
- The report authors also quoted research indicating the effectiveness of atmospheric CO_2 mitigation through CCS for annual release rates as high as 10^{-3} of the amount of CO_2 stored.

Given these statements, some subsequent researchers have used an annual release rate of 10^{-3} of the amount of CO_2 stored as the performance objective for a CCS project, while others used the “likely” value of “99% retained over 1000 years” as performance objective. It must be underlined though that none of these two figures, which differ by two orders of magnitude in terms of release rate, was recommended as a performance objective by the authors of the IPCC Special Report on CCS and by IPCC itself.

The 10^{-3} release rate should be considered cautiously, as it results from studies considering CO_2 storage sites around the world as a whole (global effects). There is therefore a mean effect behind this value, which should hence not be taken as the performance objective for specific CCS operations. As stated by the IPCC, it is expected that most sites should perform much more efficiently. Several authors (e.g. Bradshaw et al., 2005, Stenhouse et al., 2006) pleaded for the use for risk assessment purposes of much more realistic release rates from a geological perspective, for instance in the order of 10^{-7}.

Furthermore, the figures mentioned above are based either on technical and geological considerations, or on modelling of the global effects of CO_2 releases. None of them relates to the potential impacts that such a leak could cause locally on humans or on the

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[1] In this document, we use “release”, “seepage” or “emissions” to designate a movement of the injected fluid from the storage site to the atmosphere or the water column (in the case of an offshore storage), and “leakage” to designate a movement of the injected fluid out of the geological formations intended for its storage

environment and valuable resources. In other words, no quantitative threshold on leakage rates has been established at the local scale following a risk approach. Stenhouse *et al.* (2009) pointed out that "to date, […] assessments of storage projects have focussed more on the performance of the storage reservoir in terms of its ability to contain the CO_2 or at least prevent its leakage to the surface or near-surface environment, rather than determine the potential impacts of leakage of CO_2 (together with any gases such as H_2S or radon that may be transported with the CO_2) on specific environmental targets". Pearce *et al.* (2005) underlined that "repository performance criteria based on risks to human health or the environment […] might differ significantly from [an acceptable leakage rate defined in terms of the emissions reduction performance of geological storage], depending on local conditions". As an illustration of the lack of references with respect to safety, the EU Directive on CO_2 geological storage requires the operator "to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health", but does not set a limit for tolerable leakage rates or CO_2 concentrations.

Which evaluation criteria for assessing safety and integrity of a CO_2 storage site?

Based on the above, a risk-based approach should be taken to analyse whether a proposed storage site is safe. Risks should be assessed specifically for every storage site. However, so far, no methodology has been agreed and recognized worldwide as a standard for assessing risks related to CO_2 geological storage (see *e.g.* Oldenburg *et al.*, 2009, Bouc *et al.*, 2009), though various approaches were developed such as the FEP (Features, Events, Processes) approach (Wildenborg *et al.*, 2004, Savage *et al.*, 2004) or the RISQUE method (Bowden & Rigg, 2004). In addition to the methodological gap, benchmarks are needed to compute the level of risk (as defined by the combination of the severity of an adverse effect to humans or environmental assets and the likelihood of its occurrence) and to evaluate it against agreed thresholds.

Understanding and evaluating the risk caused by a leak implies knowing, in addition to its likelihood, the corresponding levels of exposure and the effects they could cause on the various targets at stake. Both points raise difficulties in the case of CO_2 geological storage. It appears indeed that the potential effects of releases on the environment (on ecosystems and, to a lesser extent, on human health) cannot yet be fully described due to some crucial knowledge gaps, described below.

Effects of exposure to CO_2

Stenhouse *et al.* (2009) highlighted the « lack of information or data on the nature of the potentially broad range of environmental impacts that might arise from elevated levels of CO_2 in the environment ».

Effects on human health

Health consequences of human exposure to CO_2 are well documented. Carbon dioxide is a biologically active gas which has effects on numerous physiological functions (breathing, chemical balance control, pH control). This is the reason why high CO_2 concentrations are toxic. The effects of CO_2 can be summed up as follows (Hepple, 2005): at or below 1% CO_2 nearly no effect is noted; chronic exposure to 1.5-3% results in physiological adaptation without adverse consequences; above 5% CO_2 irreversible effects are observed and loss of consciousness can occur; death is imminent at 30% CO_2 concentrations.

However, the currently available data are based on studies involving only healthy volunteers. No long-term epidemiological studies have been carried out to study the effects of long-term exposure to CO_2 on highly susceptible subgroups (children, elderly people, people with respiratory deficiencies) (IEA GHG, 2007).

Effects on ecosystems

Impacts of CO_2 on terrestrial, subsurface and marine ecosystems are generally poorly understood (West *et al.,* 2005). Data on CO_2 effects are only available for few taxa. Furthermore, there is a very wide range of sensitivity depending on the species and the ecological environment. Thus, it is very difficult to draw general conclusions.

Here is a summary of available information and existing knowledge gaps:

- Surface-dwelling animals: Few data are available about the toxicity of CO_2. Nevertheless, thresholds for human may be appropriate proxies for surface-dwelling animals (U.S. EPA, 2008). Generally, concentrations above 5% lead to respiratory poisoning for animals (Sage, 2002). Surface-dwelling animals can suffer secondary effects if plants are adversely impacted (U.S. EPA, 2008).
- Insects: The heart of insects is stimulated by 5% CO_2 concentrations, but it stops beating at very high concentrations. Surprisingly, this can happen without damage to the insect (Nicolas and Sillans, 1989). Thus, insects generally show higher resistance to CO_2 than other animals. However, their behaviour can be affected by very low variations of CO_2 concentrations (Sage, 2002).
- Soil-dwelling animals: They may begin experiencing negative physiological effects at 2% CO_2 and concentrations of approximately 15% could be lethal (U.S. EPA, 2008). Invertebrates response to CO_2 has been studied for some taxa (Sustr and Simek, 1996).
- Freshwater: Few data exist on the effects of increased CO_2 concentrations on lakes and rivers (IEA GHG, 2007). Aquatic animals may be adversely impacted or killed by pH variations of a few tenths (Hepple, 2005).
- Microbes: Some microbes are killed by concentrations above 10% CO_2, and 50% CO_2 has generally a significant inhibitory or lethal effect (Hepple, 2005). Experiments have been carried out at (natural or artificial) test sites where CO_2 is released. It appears that CO_2 exposure may influence microbial activities and the total number of microorganisms (Kruger *et al.,* 2009; Beaubien *et al.,* 2008; West *et al.,* 2008). However, tolerances are extremely wide. Some microorganisms (Archaea) may be enhanced by increasing CO_2 concentrations (Kruger *et al.,* 2009). Microbial population may be affected by biogeochemical changes due to CO_2 exposure, which may change nutrients availability (ex: nitrogen) and impact the whole ecosystem (IEA GHG, 2007). The effects on deep subsurface microbial populations are not well known (U.S. EPA, 2008).
- Plants: A critical threshold seems to be around concentrations of 20 to 30% CO_2 (IEA GHG, 2007). A slight increase of atmospheric CO_2 can enhance plant photosynthesis. However, an important increase of CO_2 concentration (in soil or in air) has adverse physiological effects. Plants responses have been studied at test sites where CO_2 is released (Kruger *et al.,* 2009; Beaubien *et al.,* 2008; West *et al.,* 2008). According to those experiments and depending on CO_2 exposure, impacts may range from subtle changes in vegetation diversity or composition to total disappearance of plants (die-out). Some plants appear to be more tolerant than others to high levels of CO_2 (ex: monocotyledonous).

There is no documented case of environmental impacts due to CO_2 leakage from an anthropogenic geological storage reservoir. Studies on natural sites where deep-origin CO_2 is released (e.g., Latera Caldera in Italy, Laacher See in Germany) provide interesting results. However, in these sites where CO_2 has leaked for considerable time periods ecosystems may have adapted to high CO_2 concentrations. Thus, observed impacts may not be representative of the short-term or middle-term local impacts in case of leakage from a geological storage reservoir (West *et al.*, 2008).

Exposure to CO_2 may impact ecosystems diversity, soils and crop growth, but little information is available in those areas. Nearly no data exist about the ecosystems capacity to recover following releases events. There are also very few studies of ecosystems long-term exposure to chronic concentrations (<10% CO_2) (West et al., 2005).

Few data are available on the indirect impacts of CO_2 exposure (habitat loss, changing soil pH…).

Effects on groundwater

The literature about the effects of CO_2 leakage into an aquifer used as a source of drinking water is relatively scarce so far. Most simulations for CO_2 geological storage investigate the consequences of physico-chemical reactions induced by the injection of CO_2 into the reservoir formation. The main purpose of these simulations is the understanding and the forecast of the long-term CO_2 behaviour. But waters from storage formations investigated for CO_2 storage are typically unusable for industrial or human consumption purposes because of their high salinity. Hence water quality alteration in these aquifers is not a concern and is not assessed in those studies. Concern about quality changes in drinking water aquifers following CO_2 leakage from an underlying reservoir has been addressed only recently.

Potential geochemical effects of CO_2 leakage into an aquifer are complex and widely dependent on aquifer's lithology, therefore requiring site-specific assessments. In addition to flow perturbation due to pressure changes, CO_2 leakage into an aquifer could affect:

- mineral dissolution / precipitation equilibria, thus changing water mineral composition and potentially liberating trace elements;
- metal sorption, precipitation or aqueous complex formation;
- mobilisation of organic compounds, for which CO_2 is an excellent solvent;
- microbial activity.

A study at the scale of the US territory (Apps *et al.*, 2009, Birkholzer *et al.*, 2008) identified arsenic (As), lead (Pb), zinc (Zn), barium (Ba) antimony (Sb) as potentially critical elements whose concentration in an aquifer could exceed the quality limits as a result of a release from the rock matrix, under reducing conditions (which are characteristic of most groundwaters). The rate of CO_2 leakage into an aquifer would affect the geometrical extent of groundwater contamination more than the concentration levels, which basically do not change once the CO_2 solubility limit of water has been exceeded (Zheng *et al.*, 2009).

Concentration limits for the above-cited elements, as well as pH references defining the range of acceptable acidity, exist in the requirements for potable water. The difficulty here lies in the site-specific nature of the studies required to assess water quality alteration, which research so far has not excluded.

Effects of impurities

Depending on the capture process and the CO_2 source, different "impurities" could be co-injected with CO_2 (H_2S, SO_2, NOx, Hg…). The fate of co-injected species is not well understood (IEA GHG, 2007). A CO_2 leak may act as a carrier of naturally-occurring subsurface gases (hydrogen sullfide, radon and methane). Impurities potentially have a very wide range of effects (cancer, fertility decline, malformations…) and may impact receptors by different exposure pathway (inhalation, ingestion, dermal contact, surficial contact). Though current research in various projects seeks to address this concern, insufficient information is available to assess the risks associated with gas impurities at present time (IPCC, 2005).

Exposure assessment

The effects of CO_2 (and/or impurities) depend much more on the level of exposure (concentration and duration) than on the total quantity of CO_2 released. Consequently, safety assessments should be based on the potential concentrations that could result from a leak from a CO_2 geological storage site, rather than primarily focussing on leakage rates and/or volumes. A leakage rate or volume by itself is not representative in terms of safety; it must be converted into an exposure level to evaluate the consequences it generates.

Exposure assessment is currently an important challenge because it supposes to know the behaviour and fate of the leaking CO_2 (IPCC, 2005). Little information is available in this area. The concentrations in soil porosity is often very high (nearly 100% CO_2) at natural test sites where deep-origin CO_2 is released. In the atmosphere, it seems that dispersion generally quickly dilutes CO_2 seepages. As a consequence, biological receptors are susceptible to be exposed to higher CO_2 concentrations in soil than in atmosphere (IPCC, 2005). Nevertheless, CO_2 is a high density gas which tends to migrate downwards and accumulate in low-lying areas or in confined spaces. This property may create locally high concentration zones in places lacking wind or ventilation. Only few studies so far (*e.g.* Bogen *et al.*, 2006, Chow *et al.*, 2009, Stenhouse *et al.*, 2009) have investigated the fate of CO_2 at the surface and the potential for accumulation either outdoor (*e.g.* in topographic depressions) or indoor (*e.g.* in basements). Such studies require taking account of site-specific geographic as well as meteorological conditions.

Acceptable concentration limits for human and ecosystems

In regard to human exposure to CO_2 and impurities, some standards containing exposure thresholds exist in the area of industrial hygiene, ambient air quality, hazard assessment or health risk assessment (Table 1).

	Limit value	Duration of exposure	Country/Entity	Reference
Occupational exposure limit 8h/day (Workers)	0.5 %	8h/day	Europe, United Sates, Canada	European commission, 2007; Hepple, 2005
Short-Term Exposure Limit (Workers)	3 %	15 minutes	United Sates	Hepple, 2005
Level immediately dangerous to life and health	4 %	-	United Sates	Hepple, 2005
Irreversible Effects (risk assessment)	5 %	30 minutes	France	Ministry of ecology, 2007
First lethal effects (risk assessment)	10 %	30 minutes	France	Ministry of ecology, 2007
Significant lethal effects (risk assessment)	20 %	30 minutes	France	Ministry of ecology, 2007

Table 1 – Examples of CO_2 thresholds from regulations.

Concerning ecosystems, there are only few data about the toxicity of impurities and CO_2. There is no clear definition of acceptable limit for specific ecosystems (IEA GHG, 2007). To date, neither acceptable limits nor key indicator organisms have been established. These would probably be site-specific and dependent on the use of the ecosystems.

Computation of a risk level

Thus, CCS faces the difficulty of providing a reliable estimate of the risk level due to the processes and time scales involved. Risk assessment for common industrial activities usually combines the estimated severity and probability of occurrence of an undesirable event. In the case of CO_2 storage, uncertainties about the geological medium and the long-term behaviour of the storage complex, as well as limited experience imply that any probability estimation for the occurrence of such an event is subjective and can be disputed, given the time scales considered.

Acceptable risk levels

Finally, assuming an estimation of the risk can be provided, CCS currently lacks a definition for an acceptable level of risk, expressed in terms of probabilistic number of fatalities per year for instance.

In France, a note from the Ministry in charge of Ecology, dated 16 November 2007, defines the thresholds on CO_2 atmospheric content to be considered in the risk assessment carried out for surface industrial activities (Table 1). These thresholds are designed for population; different severity categories are defined depending on the number of human beings potentially exposed to these levels of CO_2 concentration. This allows integrating CO_2 fatalities on humans in the common severity / probability grid defined for assessing whether risk caused by an industry is acceptable. It should be made clear whether these thresholds and this approach also apply to CO_2 geological storage; at the international level, similar guidance appears desirable. Nevertheless, in the case of France, the indicated values do not compensate for the lack of data for evaluating the impacts on the environment; they do not allow assessing the potential effects on other targets than humans. This comment must be mitigated however in regard to other industrial activities: although the assessment of risks caused by an industry to the environment is obviously mandatory, there is no agreed-upon methodology prescribing how to take into account potential impacts on the environment, unlike impacts on humans.

Which techniques and capabilities for monitoring CO_2 storage performance and safety?

Setting performance objectives and expecting a demonstration of them being met is not sufficient by itself; for safety to be guaranteed, it is required to be able to actually monitor in respect of these goals and to intervene in the case they are not achieved. Risk management plans should explicit the thresholds on monitoring results that should trigger corrective measures.

In the EU approach, the two main goals for CO_2 storage are that CO_2 must be stored permanently in such a way that any adverse impact to the environment and human health could not occur in a normal situation. This implies that:

1. Monitoring and reporting of the stored CO_2 must inform on the performance of the storage, i.e. quantify, if any, vented and fugitive emissions from injection and/or from EOR operations, and leakage of CO_2 from the storage reservoir in the geological medium;
2. In case of leakage, the operator should be able to:
    a. Identify and quantify the impacts and inform, in the monitoring report, on the impacted targets ("physical environment", flora, fauna and humans) and the level of impact ;
    b. Mitigate these impacts according to the remediation plan.

The European Commission issued a Decision on the 8th June 2010 regarding monitoring and reporting guidelines for greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide under the EU Emissions Trading Scheme (EU ETS)[2]. According to these guidelines, monitoring dedicated to emissions accounting shall start in

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[2] As laid out in Directive 2003/87/EC establishing a scheme for greenhouse gas emission allowance trading within the Community.

the case that any leakage results in emissions to the air or release into the water column in the case of offshore storage.

But the underground cannot be managed as a classical physical medium because of the lack of tools allowing a continuous description of its different components. This is the reason why probabilistic approaches may be necessary. For the same reason, with the currently available tools, not all leaks that could occur in the geological medium could be identified, because of the insufficient resolution of monitoring methods.

In the short term and during operations, it is usually considered that the main risk of leakage from a geological storage site is associated with the failure of the features which intersect the storage unit (injection, observation or abandoned wells) or unsuited operating conditions (injection pressure too high) (*e.g.* Damen et al., 2003; Bowden and Rigg, 2004; Oldenburg et al., 2009). Proper monitoring of the installations will thus make it possible to guarantee that a possible escape will be detected as soon as possible and to start fast and effective remediation actions (well work-over, casing substitution; injection pressure decrease or even pumping of the injected CO_2). In some cases, ground deformation monitoring by remote sensing is a useful method to detect an anomalous behaviour of the storage complex.

In the longer term, the risks of seepage are primarily associated with a failure of the geological containment or of the abandoned wells. These seepages can then occur anywhere in the storage unit and the volume of gas escaping from the reservoir could be sufficiently low to be detected only a long time after the start of the escape. In this case, the main issues are (1) leakage / seepage detection, and (2) leakage / seepage quantification.

Leakage detection will be site-dependant. For instance, a recent study in the case of CO_2 injection in a French carbonate reservoir seems to demonstrate that the 4D seismic detection threshold would be in the order of 100,000 t of CO_2. At the opposite end, in the case of the Sleipner CO_2 storage, the 4D seismic detection threshold is likely 4000 m^3 (or 2500 t). Other geophysical methods, such as gravity or electrical-electromagnetic, could be able to produce a realistic quantitative assessment of the mass of CO_2 in place, but they are still at the research stage.

The most accurate monitoring plan will certainly be a combination of physical and chemical techniques. Pressure monitoring at the injection well will allow the detection of any abnormal behaviour of the stored CO_2, and sampling in a control aquifer immediately overlying the storage reservoir will allow detecting any modification of water chemistry and pressure. These two techniques will be able to alert on a leakage occurrence. But the location of the leak point and quantification of the released CO_2 are more complex. No real technical solution is available currently except a very costly geological, geochemical and geophysical survey.

In summary:

- Quantification of CO_2 in place needs an integrated approach using a mix of different techniques: geophysical surveys from the surface and downhole measurements in observation wells, geophysical and geochemical logging, gas and fluid sampling at different depths and *in situ* monitoring with permanent sensors;
- Several geophysical techniques are not really able to detect dissolved CO_2,
- Reliability of the permanent sensors for long period of time is certainly not demonstrated. ,
- The use of airborne and remote sensing techniques is still under development.

Conclusion

Besides the lack of a risk assessment methodology tailored for CCS, gaps in knowledge concerning the environmental impacts of CO_2 leaks, or the difficulties to calculate a reliable risk level based on the probability and magnitude of exposure to elevated CO_2 or impurities concentrations, there is a need for determination of either acceptable risk levels or acceptable leakage rates from CO_2 geological storage sites.

It is emphasized that performance standards (in terms of fraction of CO_2 kept away from the atmosphere) are only loosely connected to safety standards (in terms of potential adverse consequences that could occur from a CO_2 release). Indeed safety assessments have to be based on potential exposure. It necessitates converting fluxes and volumes into concentrations, which depend on the conditions of exposure of the vulnerable assets. Exposure is then conditioned by the release rate and/or volume, but not by the size of the storage. Therefore, if reporting a release rate to the total mass of CO_2 stored in the reservoir has a sense in terms of national greenhouse gas reduction commitment or in respect of individual quota obligation, it makes no sense, in terms of safety, to do so for a leakage flux leading to critical exposure. The percentages (fractions) of the amount stored stated as performance standards have to be considered as mean objective for the whole of the storage sites and are not relevant to local safety issues. Moreover, they do not rely on a geological basis.

Monitoring for health and safety is very different to monitoring for storage integrity and greenhouse gas accounting. The methodologies, the equipment, the costs and the objectives are quite different from each other. Monitoring for safety can be done with less precision than for greenhouse gas accounting but it needs to have wide coverage and in real time. Most groundwater, soil and air monitoring methods measure concentrations, not fluxes or volumes (total amount), which poses the problem of whether safety/performance assessment criteria should be site specific, namely concentration and time of exposure, or global, based on leakage flux and/or volume, or both.

Regulation requirements for performance-based standards for storage site safety and integrity

The safety and integrity of CO_2 storage will have to be guaranteed by the various regulations in place or to be defined in order to manage this activity. This one can be divided into five principal stages:

- Site identification phase: selection and qualification (exploration)
- Design and construction phase – drilling and baseline monitoring
- Operational phase - injection, monitoring and reporting,
- Post closure phase - monitoring and reporting,
- Post abandonment phase - monitoring and reporting as necessary.

For these different phases, the regulator faces two major options:

1. to define as precisely as possible the different thresholds that operators will have to meet (means and resulting obligations), which is a prescriptive-based approach; or
2. to define the main goals attributed to an activity in term of impact and to ask the operator for the demonstration that he will meet these general goals (resulting obligation), which is a performance-based approach.

EU approach

The EU approach is presented hereafter as an example.

The EU Directive for CO_2 geological storage defines in its first article the main goal for any operator who would propose to store CO_2: "*The purpose of environmentally safe geological storage of* CO_2 *is permanent containment of* CO_2 *in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health*."

But neither this Directive, nor the Guidance Documents that support its implementation (European Commission, 2011), never define what could be an acceptable risk through the definition of particular values or thresholds, as the leakage rate or concentration (see chap. 2.1) or the CO_2 purity, and so on.

In this case, the regulator is waiting for results that will demonstrate the absence of risks, and in case of abnormal processes, the complete management of their impact through adapted remediation actions.

Annexes can be integrated in this type of regulation that define the minimum requirements as intermediate results considered being essential.

The CCS field is recent, so that dedicated industrial best practices are still not mature, especially with respect to long term CO_2 containment. At the opposite end, the EU Directive of the European Parliament and the Council on industrial emissions (Integrated Pollution Prevention and Control, IPPC) is a very detailed directive. One of the main elements concerns the achievement of environmental improvements while at the same time ensuring cost-effectiveness and encouraging technical innovation.

The IPPC Directive covers emissions to air from industrial installations that represent a large share of total emissions of key pollutants. The central element of such an approach is the implementation of Best Available Techniques (BAT). This is defined as using established techniques which are the most effective in achieving a high level of environmental protection as a whole and which can be implemented in the relevant sector under economically and technically viable conditions, taking into account the costs and advantages. An information exchange on BAT is being organized by the Commission with Member States and other stakeholders to establish BAT reference documents (BREFs) indicating what is regarded as BAT at EU level for each industrial sector. The Directive defines all the concerned chemical elements, and defines for each element or molecule, the acceptable thresholds on emission rates.

In this case, performance standards are published and known. The regulator has to monitor and control the respect of all these extensively defined recommendations.

International regulatory review

A gap oriented review was carried out in 2008-2009 under the EU-funded STRACO2 project [3], with the goals of supporting the development and implementation of a comprehensive regulatory framework for CCS in the European Union and of building a basis for EU-China cooperation on CCS. In addition to regulations (*cf.* Table 2), a number of projects were reviewed and a stakeholders' opinion survey was conducted by STRACO2 team.

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[3] STRACO2 consortium:

- European members: BRGM, World Business Council for Sustainable Development, TNO, Mälardalen University, KTH – Royal Institute of Technology;
- Chinese members: DEVELOPMENT Solutions, The Administrative Centre for China's Agenda 21, Institute of Engineering Thermo-Physics, Institute of Policy and Management

Title	*Country / Entity*	*Year of Publication*
Directive 2009/31/CE of the European Parliament and of the council on the geological storage of carbon dioxide and amending Council Directives 85/337/EEC, Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC and 2008/1/EC and Regulation (EC) No 1013/2006. April 23, 2009	Europe	2009
Energy bill – Chapter 3: Storage of carbon dioxide.	United Kingdom	2008
London Protocol - Risk assessment and management framework for CO2 sequestration in sub-seabed geological structures. LC/SG-CO2 1/7, annex 3.	International Convention	2006
London Convention - Final draft specific guidelines for the assessment of carbon dioxide streams for disposal into sub-seabed geological formations.	International Convention	2007
OSPAR guidelines for Risk Assessment and Management of Storage of CO2 Streams in Geological Formation. Reference Number: 2007-12.	International Convention	2007
US-EPA - Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO2) Geologic Sequestration (GS) Wells.	U.S.	2008
US-EPA - Using the Class V Experimental Technology Well Classification for Pilot Geologic Sequestration Projects – UIC Program Guidance (UICPG # 83) March 2007.	U.S.	2007
Storage of Carbon Dioxide in Geologic Structures – A Legal and Regulatory Guide for States and Provinces – Task Force on Carbon Capture and Geologic Storage – September 25, 2007.	Interstate Oil and Gas Compact Commission	2007
Washington State Legislature – Chapter 173-218 WAC – Underground injection control program.	U.S. Washington State	2008
State of Wyoming, House Bill No. HB0090 – Carbon Capture and sequestration.	U.S. – State of Wyoming	2008
Australian Regulatory Guiding Principles - Ministry Council on Mineral and Petroleum Resources.	Australia	2005
Draft Offshore Petroleum Amendment (Greenhouse Gas Storage) Bill 2008. Overview. Reader's guide to exposure draft	Australia	2008
Amendments of the Law relating to the prevention of marine pollution and maritime disaster.	Japan	2007-2008

Table 2 – Regulatory documents reviewed under the STRACO2 project

In regard to safety, the main gaps and recommendations from the STRACO2 project are as follows (STRACO2, 2009):

- The regulatory documents assign goals rather than means to achieve them; they contain few technical criteria such as indicative or thresholds values. Because of the possible future technological developments and the "competition principle", the legislator does not recommend any technique for the acquisition of requested knowledge or parameters. The published frameworks require an application for a licence; it can be anticipated that requirements for each individual project will be set in these permits, given site-specific considerations. Indeed, the risk scenarios to consider, the adequacy of monitoring techniques or the operational parameters, to cite a few, largely depend on site-specific conditions. Moreover, lack of experience about CO_2 storage makes difficult the establishment of criteria at a generic level, and it is probably desirable that regulatory frameworks remain flexible to technological and knowledge developments. Nevertheless, the opinion survey carried out by STRACO2 demonstrated that stakeholders expect from a CCS regulation the setting of precise requirements, commonly accepted standards, guidelines or even techniques, in the field of site characterisation, site closure, risk assessment, emergency measures, monitoring, etc.
- The level of detail for site selection requirements or operational parameters varies among publications; but very few evaluation criteria can be found to determine what is an appropriate site, due to the site-specific nature of the assessment.
- There is a lack of an internationally recognised method for assessing and managing the risk posed by CO_2 geological storage and of quantitative criteria for characterising an acceptable risk. In most cases, the acceptance reference consists of a qualitative statement of the endpoint of the risk assessment. Imprecision about the time scales to be considered was emphasized as well. The project consortium therefore called for pursuing R&D and for the development of harmonised technical guidance as well as metrics on that topic.
- One of the major gaps found in the regulations relates to the impurity issues, with only the Japanese law for offshore storage setting a figure (99%) as criterion to define an acceptable composition for the injected CO_2 stream.
- Recognising the work done in various research projects on monitoring tools and methods, the consortium nevertheless stressed, from the stakeholders' survey outcomes, the development of commonly accepted best practice standards for CO_2 storage monitoring as a foremost expectation from regulators and a requisite for CCS investment.
- There is a need for regulations to require from an operator a plan for mitigation and remediation in the case of any failure of the storage, in order to meet the performance and safety objectives. The project suggested the development of guidelines for emergency measures and remediation actions for CO_2 geological storage.
- The STRACO2 consortium pointed out the lack in the existing regulations of clear expectations and quantitative references for demonstrating that a site can be abandoned, while acknowledging the site-specific nature of such process. Standards for site closure and abandonment were seen as major needs in the stakeholders' survey, and building on the lessons from early CCS projects was recommended.

Since then, the IEA published a CCS Model Regulatory Framework (IEA, 2010[a]). It addresses the key issues listed in Table 3. This model framework does not specify methods for assessing and managing risks, and does not provide reference values for evaluating risks or leakage rates.

Many regulatory developments have taken place over the last few years, as testified by the legal and regulatory reviews carried out by the IEA (2010b, 2011). To our knowledge, these developments do not substantially address the above comments from the STRACO2 project. However, elaborating requirements for long-term security and liability of storage sites, which appear to be one of the most complex aspects of the regulation of CO_2 storage activities, is currently identified as a key task by numerous countries or regions regulators (IEA, 2011). Long-term security is particularly challenging because authorities need to have evidences that the site is behaving as expected and that the predicted behaviour of the site is acceptable (IEA, 2011). In most of the regulations that deal with the long-term behaviour, it is the responsibility of the operators to demonstrate that the CO_2 storage is behaving in a predicable manner and that no significant environmental or health risks exist. Some additional information is also often required depending on the specificity of each site (formation, volume injected, the predominant trapping mechanisms…). Nevertheless, it is worth underlining that detailed technical requirements and performance standards for storage site safety that need to be met before a site closure are still to come.

Broad regulatory issues	1.	Classifying CO_2
	2.	Property rights
	3.	Competition with other users and preferential rights issue
	4.	Transboundary movement of CO_2
	5.	International laws for the protection of the marine environment
	6.	Providing incentives for CCS as part of climate change mitigation strategies
Existing regulatory issues applied to CCS	7.	Protecting human health
	8.	Composition of the CO_2 stream
	9.	The role of environmental impact assessment
	10.	Third-party access to storage site and transportation infrastructure
	11.	Engaging the public in decision making
CCS-specific regulatory issues	12.	CO_2 capture
	13.	CO_2 transportation
	14.	Scope of framework and prohibitions
	15.	Definitions and terminology applicable to CO_2 storage regulations
	16.	Authorisation of storage site exploration activities
	17.	Regulating site selection and characterisation activities
	18.	Authorisation of storage activities
	19.	Project inspections
	20.	Monitoring, reporting and verification requirements
	21.	Corrective measures and remediation measures
	22.	Liability during the project period
	23.	Authorisation for storage site closure
	24.	Liability during the post-closure period
	25.	Financial contributions to post-closure stewardship
Emerging CCS regulatory issues	26.	Sharing knowledge and experience through the demonstration phase
	27.	CCS ready
	28.	Using CCS for biomass-based sources
	29.	Understanding enhanced hydrocarbon recovery with CCS

Table 3 – Key issues relating to CCS regulatory frameworks

In addition to regulatory developments, Guidelines for Selection, Characterization and Qualification of Sites and Projects for Geological Storage of CO_2 have been developed by a Joint Industry Project led by DNV (2009). These guidelines constitute a framework for an appropriate management of a CO2 storage site and of the related risks. In addition to careful site selection and characterisation, they emphasise the need, in an iterative process, to identify and rank uncertainties and risks, and to develop appropriate monitoring and risk reduction measures. However, they do not specify quantitative values for evaluating risks. In the guidelines, “it is proposed that the performance targets shall be tailored to the unique characteristics of each site” (DNV, 2009). These “project specific performance targets” should result from a dialogue between the project developers and the regulator(s).

Conclusion

In conclusion, we can probably assume that the integrity and performance assessment for CO_2 storage will be primarily based on:

- the characterisation of the storage complex;
- the capacity of simulation tools to reproduce and predict the behaviour of the injected CO_2 and the integrity of the complex;
- the ability of the monitoring techniques to detect, locate and quantify the volume of CO_2 present in the underground and the ability of monitoring techniques and technologies to detect and quantify leaks.

We can expect that future progress will allow the development and improvement of new tools in order to reach this objective relatively easily. And in the cases in which geophysical techniques from surface would not be adapted for site-specific reasons, the possibility of obtaining information directly from the sub-surface gives a guarantee to the regulators and the concerned public.

However, concerning safety assessment, the issue is more complex.

- On the one hand, stakeholders (governments, industry, public, NGOs) are waiting for more precise values and thresholds that could provide the framework for monitoring and control of safety criteria.
- On the other hand, the specificity of activities related to geological media cannot allow the precise and continuous description of the solid space in which one intends to store CO_2. Combined with the available data on CO_2 acceptable exposure (concentration and duration), it causes difficulties in defining realistic general values or thresholds that industry will have to meet and that governments will have to regulate.
- Even though *"the indications are also that the accident hazard posed by a CO_2 storage site, whether from rupture at injection or from post-injection leakage, is unlikely to be significant"* (Discussions of the European Parliament, 16/12/2008, Andri Pielsbag *Statement by the Commission on whether carbon dioxide should be a named substance with suitable thresholds in a revised Seveso Directive*), and particularly if the initial phases of the process (selection and qualification of CO_2 storage site) are well carried out, it will be difficult to reach local and global consensus on risks posed by any CO_2 storage project without a very important research effort, in order to lower uncertainties that remain for this important issue.

This is why regular revisions of the existing regulations will be necessary in order to integrate the results of the first research pilots and industrial demo-plants.

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