Monitoring Technologies and their Characteristics in CCS

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Japan CCS Co; Ltd.

Preface

In order to carry out geological storage of CO_2 in CCS projects, long-term monitoring of the injection status, etc. is required; starting with a baseline survey in the preparation phase, during the CO_2 injection operation period, and after the completion of injection operation until certain conditions are met.

Japan CCS Co., Ltd. ("JCCS") established the "Advisory Committee for the Tomakomai CCS Demonstration Project" ("Advisory Committee") to examine the technical issues to be resolved when commissioning and implementing the "Tomakomai CCS Large-scale Demonstration Project" ("Tomakomai CCS Demonstration Project") from the Government and others, and has obtained advice from experts. The Tomakomai CCS Demonstration Project has been continuously monitored for about 12 years, from the preparatory stage to the present after achieving 300,000 tonnes of injection, with advice and confirmation from the Advisory Committee.

In response to developments towards the social implementation of CCS, such as the formulation of the CCS long-term roadmap by the Government, the enactment of the CCS Business Act and the selection of Advanced CCS Projects, a "Subcommittee on Ideal Monitoring with a view towards the Future Social Implementation of CCS" ("Monitoring Subcommittee") was established within JCCS in 2021 as a subordinate body of the Advisory Committee. The subcommittee examined the ideal form of monitoring in Japan and based on the experience of the Tomakomai CCS Demonstration Project and considering the results of surveys of overseas trends, compiled a summary. An overview of the results was also presented at the 2nd Carbon Management Subcommittee (Ref. 4, November 6, 2023) in the form of a 'Proposal Outline' of the ideal form of monitoring.

In addition to the above, a booklet "Monitoring Technologies in CCS and Their Characteristics" has recently been produced to help more people understand what monitoring technology is and what it can tell us.

This booklet has been compiled as clearly and briefly as possible to make it understandable to those unfamiliar with technical terminology and aims to be a useful guide for corporate decision-makers, policy-makers and the wider public.

For more detailed technical content, please refer to the "CO_2 Geological Storage Technology Casebook", which has already been published in part by the Carbon Dioxide Geological Stogy Research Association.

We would like to take this opportunity to thank the expert members of the Advisory Committee and the Monitoring Subcommittee as well as their affiliations for their assistance in the preparation of this booklet.

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What is CCS?

CCS (Carbon dioxide Capture and Storage) is technology to "capture and store carbon dioxide". Global warming measures are now urgently needed. Many large-scale CCS projects are already in operation around the world, and the environment for commercialization is being developed in Japan as well.

A key global warming countermeasure

CCS is a technology for capturing carbon dioxide and sequestering it deep in the subsurface. It is attracting attention as a key countermeasure against global warming, as it can significantly reduce the amount of carbon dioxide emitted into the atmosphere from factories, thermal power stations and oil refineries.

Many countries are now aiming to become carbon neutral by 2050 (i.e., to balance the emission and absorption of greenhouse gases such as carbon dioxide so that emissions are effectively zero). However, it is not possible to switch from fossil fuels to other energy sources right away, and some industries find it difficult to change to processes that do not emit carbon dioxide. This means that we must curb global warming which is occurring rapidly while using fossil fuels, and measures to do so are urgently needed. This is why there are high hopes for CCS, which can directly reduce carbon dioxide emissions.

How CCS works

Carbon dioxide is trapped in geological formations approximately 1000 to 3000 meters deep in the subsurface. There must always be a pair of formations: a reservoir, such as sandstone, which has many pores and allows carbon dioxide to enter easily, and a cap rock, which overlies the reservoir and prevents carbon dioxide from passing through it. The cap rock is a formation of fine particles such as clay that acts as a lid to prevent carbon dioxide from leaking. Ideally, the reservoir should be as thick and widely distributed as possible, so that as much carbon dioxide as possible can be contained.

In CCS, a well is drilled into the reservoir and carbon dioxide captured from the flue gas of a factory or other source is pumped in under pressure. This is called 'injection' and the well for this purpose is called an 'injection well'. In this case, the subsurface pressure and temperature enables the storage of carbon dioxide at a volume approximately 1/300th that of the earth's surface.

Applying oil and natural gas development technology

The technology of 'injecting carbon dioxide in the subsurface' is not new in itself and has been used for some time in oilfield development. The method of recovering oil by injecting carbon dioxide into the subsurface (enhanced oil recovery: EOR) has already been used since the 1970s. The conditions for reservoir and cap rock pairs in CCS also apply to oil and gas fields. Therefore, technology for finding oil can be applied to finding suitable locations for CCS. Other technologies such as drilling injection wells, injecting carbon dioxide and transporting high-pressure gas through pipelines are similar to oilfield development technologies.

In this way, CCS projects are being implemented in many parts of the world, applying various technologies developed in oil and natural gas development and adding new technologies to them.

Commercialisation is accelerating around the world.

In 1996, Norwegian oil companies were the first in the world to commercialize CCS. The trigger was the Norwegian government's decision to impose a carbon tax on carbon dioxide emissions. This led to the injection of carbon dioxide separated from natural gas in the Sleipner gas field back into the subsurface.

Subsequently, the introduction of carbon taxes in European countries and elsewhere, the adoption of the Paris Agreement at COP21 in 2015, and the creation of the '45 Q' tax credit system in the USA as an incentive for carbon capture, rapidly advanced the trend towards CCS commercialization. Today, many large-scale CCS projects are in operation in the USA, Canada and Europe.

Japan's moves to improve the business environment.

In Japan, CCS demonstrations have so far been carried out in Nagaoka, Niigata Prefecture (CO_2 injection demonstration) and in Tomakomai, Hokkaido (CCS demonstration). In Nagaoka, 10,000 tonnes of carbon dioxide was injected in 2003 ～ 2005, and in Tomakomai, 300,000 tonnes in 2016 ～ 2019, demonstrating that CCS is a safe and secure system.

More recently, there has been a growing push to commercialise CCS: in March 2023, the Ministry of Economy, Trade and Industry (METI) published the final summary of the 'CCS Long-term Roadmap Study Group'. As one of its concrete actions, the Japan Energy and Metals National Corporation (JOGMEC) selected nine 'Advanced CCS Projects' with the aim of starting operations by 2030. Furthermore, the 'Law on Carbon Dioxide Storage Projects (CCS Business Act)' was passed and promulgated by the Diet in May 2024. Thus, the environment is steadily being developed for CCS to take root in Japan as a new industry. The target is to reduce carbon dioxide emissions by 120 million tonnes～ 240 million tonnes per year by 2050 through CCS, and once CCS business is in full swing, we will make great strides towards achieving carbon neutrality by 2050.

Objectives of Monitoring.

CCS projects require long-term monitoring (surveillance) from the preparatory phase of operations to the end of operations.

It is important to confirm the safe storage of carbon dioxide based on data, while at the same time, it is also very important to explain the confirmed details in an easy-to-understand manner and gain the understanding of the local community.

Why is monitoring necessary?

Safety and security are the highest priorities for CCS projects. CCS projects can last for decades and therefore require monitoring to ensure that they are operated properly and that the data obtained is shared with stakeholders, such as regulators and local residents. There are three main reasons why monitoring is necessary.

Reasons Why monitoring is necessary?

(1) To show that carbon dioxide is being stored as planned.

(2) To demonstrate that CCS projects are carried out safely in accordance with the law.

(3) To gain the understanding of local residents and other stakeholders.

To gain local understanding.

To store carbon dioxide stably underground, the underground structure is key. There are international standards, such as those set by ISO (International Organisation for Standardisation), for selecting CCS sites. Specifically, these include having a cap rock above the storage layer (the reservoir), no major faults nearby, and no history of major earthquakes.

As sites that meet these criteria are selected, it has been confirmed through domestic and international cases that even when carbon dioxide is actually injected into the subsurface, associated risks such as earthquakes or carbon dioxide leakage are extremely low.

Nevertheless, people generally tend to feel uneasy about things they do not understand and are more likely to accept things they can understand. Since CCS is still not widely known in Japanese society, it is natural that many people feel may uneasy. This is precisely why it is most important to explain its safety in a clear and understandable manner. When we ask the general public for their opinions on CCS, the following concerns are often raised:

(1) Will the carbon dioxide leaking out? **Can you tell If it is leaking, ?**

(2) Is it possible to know accurately where and how much carbon dioxide is in the ground?

(3) Could the injection of carbon dioxide into the ground cause earthquakes?

In order to gain the understanding and cooperation of the local community, it is important to investigate the above items through monitoring and to allay their concerns. It is important to demonstrate that the project operator has the technology to investigate the subsurface, that it is monitoring the condition of the injected carbon dioxide to ensure that it is not leaking, and that scientific and correct communication based on data is conducted. Gaining local understanding through such efforts will be the foundation for stable operations.

Showing that CCS projects are being carried out safely

Specifically, explanation is conducted regarding three categories.

1) Operational conditions (whether carbon dioxide is being injected safely?)

The injection system, including the wells and equipment that pump carbon dioxide into the subsurface, is monitored for any issues. As the pressure in the formation near the injection wells increases once operations begin, the system is also monitored for unexpected changes in pressure, temperature and vibrations.

2) Storage conditions (i.e. whether the carbon dioxide is retained in the reservoir).

Monitoring is conducted as to whether the carbon dioxide injected into the reservoir is stored in the expected area of the reservoir, to what extent it has penetrated into the cap rock, as well as to confirm that it has not moved closer to a fault. Also, careful monitoring of any changes that could lead to leakage is conducted.

(3) Environment (whether there is any negative impact on the environment of the living area).

Monitoring is conducted as to whether the carbon dioxide will leak to the surface or into the sea, and if so, what the impact would be. Though it is almost inconceivable that it would leak into the living environment as the appropriate facilities (sites) have been selected in the first place, monitoring is necessary to enhance the safety of the project and to respond to public concerns.

"Seepage"and "Leakage"are different, and what is the difference?

In CCS monitoring, it is important to distinguish between ‘leakage’ and ‘seepage’ rather than simply referring to them as ‘leaks’. The Items are defined below.

“Leakage” refers to the movement of carbon dioxide into the storage complex (area outside the pre-planned storage area) predicted by simulation, etc.

“Seepage” refers to the intrusion of carbon dioxide into groundwater used by people or its outflow from the ground or sea.

If “leakage” is detected, it may take several years or decades for it to lead to “seepage”. In practice, by monitoring for “leakage” and taking appropriate measures when the risk of leakage is confirmed, issues can be resolved before they escalate into “seepages”. Therefore, distinguishing between “leakage” and “seepage” and identifying early signs of “leakage” in advance is the most effective approach. This allows “seepage” monitoring to be positioned as a ‘preventive measure’ implemented as needed.

Overview of monitoring methods.

What monitoring technologies are actually available to visualize the deep subsurface which cannot be observed directly?

Typical methods and case studies will be presented to illustrate how project operators and stakeholders can benefit from being able to respond and explain based on the data obtained.

Determining various conditions from temperature and pressure

Temperature and pressure are extremely important items in CCS monitoring. By examining the temperature and pressure in injection wells and reservoirs, various conditions can be determined.

For example, if the expected pressure drops significantly, it is possible that carbon dioxide is leaking from somewhere, whereas if the pressure increases too much, it could lead to the destruction of the cap rock. In such cases, measures can be taken before it becomes a major problem such as stopping the injection and analyzing the cause of the leak, checking for problems in the well itself, and adjusting the amount of injection to protect the cap rock.

Various methods of using wells to determine subsurface conditions.

To investigate the subsurface conditions around a well, various observation instruments such as temperature sensors, pressure sensors and seismometers can be installed in the injection well for continuous observation. On the other hand, there are also methods whereby observation equipment is lowered into the well as necessary and gradually raised to collect detailed data, such as whether there are any carbon dioxide pathways such as cracks in the walls of the well, or the state of the strata around the well.

Recently, optical fiber sensing technology has attracted attention as a method for continuous observation of conditions around wells. If fiber-optic observation equipment is installed when the well is drilled, it is possible to obtain real-time data on temperature, strain, vibration, etc. over a long period of time, and monitoring time and costs can be significantly reduced, so there are expectations that the technology will be put into full-scale practical use.

Other methods include remote sensing to determine whether subsurface pressure is pushing up and deforming the surface, or directly measuring carbon dioxide concentrations near the well to determine if there are any leaks created along the well.

Investigating the subsurface with seismic surveys.

Seismic exploration is a technology used to determine the condition of subsurface strata that cannot be directly observed. This technology is also used to identify strata suitable for CCS and to determine how much carbon dioxide can be stored in the strata. Additionally, by comparing 'baseline data' collected before injection begins with 'data obtained after injection starts' through monitoring once the project commences, seismic exploration enables the monitoring of changes in the subsurface.

The mechanism of seismic exploration is similar to that of ultrasound echocardiography or 3D-CT scans used in hospitals. Just as sound waves are reflected to view the inside of the body, seismic exploration uses the same principle to view cross-sections of rock layers (2D seismic exploration) or to visualize the subsurface in three dimensions (3D seismic exploration).

Through seismic exploration, it is possible to determine whether carbon dioxide is properly retained in the reservoir, and by repeating the seismic surveys over time, it is possible to predict how the carbon dioxide will move.

How the carbon dioxide is spreading.

Because the reservoir is not completely isolated from the outside world like a glass container, the carbon dioxide that is injected into the reservoir (e.g., sandstone layer) spreads out like a mist from the bottom of the injection well. Instead of spreading out neatly in concentric circles, the carbon dioxide will flow unevenly into areas where there are many pores and where it is easy to enter. If the seismic surveys confirm that the carbon dioxide is spreading out within the expected range, the project operator can continue the CCS project with peace of mind.

Cost of seismic surveys (cost)

Seismic surveys are essential for CCS projects, but they are extremely costly. In particular, the initial survey of suitable storage sites (basic survey) and site characterization before starting a project can be expensive, costing several hundred million yen or more, depending on the scope of the survey. However, subsequent monitor (confirmation) seismic surveys can be carried out on a smaller scale, depending on the objectives.

The cost of monitor surveys can vary greatly depending on the location, whether it is offshore, coastal or onshore, but in some cases the cost can be minimized by limiting the scope, using 2D surveys or reducing the frequency, so that monitor surveys can be planned within economically reasonable limits.

Monitoring as "insurance".

Monitoring also serves as 'insurance' to protect operators and local residents. For example, if “seepage” of carbon dioxide were to occur, it would not only cause inconvenience to local residents but would also cost a great deal of money to deal with and could even cause social damage as a “seepage” accident.

However, if “leakage” is monitored and dealt with appropriately before “seepage” occurs, it can be dealt with at little cost and trust can be maintained with the local community. If “leakage” is detected, “seepage” incidents can be avoided by taking action such as stopping injection or reducing pressure.

In this way, there are many benefits to be gained by considering monitoring costs as 'insurance'.

Interest in induced earthquakes

As Japan is a seismically active country, there is strong interest in whether CCS will cause induced earthquakes and whether earthquakes will cause carbon dioxide leakage.

In the world's first large-scale CCS project, Sleipner (Norway), 27 years have already passed, but no induced earthquakes have occurred. And at the Tomakomai CCS demonstration site, we know that the reservoir pressure has hardly changed even after the injection of carbon dioxide. And to date, no induced earthquakes have ever been observed.

In addition, the geological formations targeted by CCS projects in Japan are considered less prone to induced earthquakes than those in other countries. The reason for this is that the geological formations in Japan that are suitable for storage are of a relatively recent age, which are relatively resistant to cracking and can expand and contract. It can also be said that they are less prone to earthquakes because they deform without cracking when carbon dioxide is injected into them.
On the other hand, the Japanese archipelago and its surroundings lie on multiple plate boundaries. The selection of suitable storage areas must avoid active faults, which makes the selection of target areas even more important when compared to overseas.

On 6 September 2018, the Hokkaido Eastern Iburi Earthquake (magnitude 6.7) occurred, and the Tomakomai CCS Demonstration Center also observed a tremor with an intensity of 5 minus on the Japanese seismic scale. No abnormalities were found in the aboveground facilities, and monitoring of reservoir temperatures and pressures confirmed that no leakage of carbon dioxide had occurred. In addition, we were able to show the data accumulated from the monitoring and the CO_2 behavior simulation to the local residents and other stakeholders and have them understand that the carbon dioxide injection was not the cause of the earthquake.

Local residents and other stakeholders to understand that there is "no"

Monitoring targeting the marine environment.

There is great social concern on the impact of CCS on the environment, and the Tomakomai CCS Demonstration Project is introduced as an example. Tomakomai has a thriving fishing industry, and some people were concerned that the sound and vibration emitted by seismic surveys would reduce the number of fish, or that seepage of carbon dioxide would make the sea acidic, killing fish and crustaceans. Therefore, we took samples of organisms such as surf clams, seawater and sea bottom sediments, and observed the sea with unmanned probes to survey the marine environment. As a result, it was confirmed that there was no carbon dioxide seepage and that there was no impact on living organisms.

Environmental impact assessments based on marine environmental surveys are difficult in some respects, as they are heavily influenced by natural fluctuations due to seasonal and ocean currents. As the Tomakomai Project was a demonstration project and not a commercial project, extensive monitoring was carried out with the aim of determining from the results what monitoring was necessary and what could be excluded.

As a result, it has been concluded that marine environmental surveys, which are highly sensitive to natural variability, are unsuitable as a means of continuous monitoring for seepage. By ensuring that local communities understand that surveys of the marine environment can be conducted at any time if necessary, and by checking for leakage in advance, it is considered that in many cases, it is possible to exclude marine environmental surveys for the detection of seepage from routine monitoring.

Management of CCS facilities after site closure

In CCS projects, once the carbon dioxide storage volume reaches the target, the injection is stopped and the facility (site) is closed. After that, monitoring must continue to ensure that the stored carbon dioxide does not leak, but as it is difficult to ask private operators to manage the site permanently, it is being considered to transfer security management after a certain period to public entities such as the Japan Energy, Metals and Minerals Corporation (JOGMEC).

Monitoring technologies and their characteristics

In describing individual monitoring techniques, the subject and the technology are described assuming monitoring in an area in Japan.

Assumed Monitoring Plan in Japan (Area A).

When CCS is carried out in areas such as coastal areas, offshore areas, areas surrounded by faults and onshore areas in Japan, the most appropriate monitoring depends on the specific location. This section assumes 'Area A' as a representative area and gives specific examples of when and where standard monitoring should be carried out and what technologies should be applied. 'Area A' is assumed to be an area such as Tomakomai, where CO_2 is injected from onshore into the coastal sub-seabed.

Subject.	Item		Applicable technology/measurement	Before Press-in (Duration required).	under pressure: normal times	under pressure: time of risk concern scenario	After stopping press-fitting	After transfer or abandonment of mine
operational status	Injection Fluid (composition, flow rate, concentration)		Press-in volume measurement		○			
	Top_of_the_wellbore (pressure, temperature)		Temperature and pressure gauges, optical fibre		●			
	Bottom_of_the_wellbore (pressure, temperature)		Temperature and pressure gauges, optical fibre	baseline	●		○**	△
	well integrity e.g. annulus pressure)		Pressure gauges, galvanometers, fibre optics.	baseline	●			
			Seismographs, fibre optic.	baseline	○		○**	△
Stored. CO_2 status.	Understanding CO_2 behaviour (distant ↕)	wellbore area ~10m.	Logging, wellbore geophysical surveys, optical fibre	baseline	●			
		Around the wellbore ~1km	Well geophysical surveys, 2D/3D Elastic waves, fibre optics	baseline	●			
		wide area ~ several km	2D/3D seismic waves, optical fibre	baseline	●		○**	△
	Strata water analysis		Compositional change and quantification	baseline		△		
	Surface displacement (mainly onshore)		GPS positioning, In-SAR	baseline		△		
Environmental impact. Implemented according to risk).	marine environment (as necessary)	water quality	Manned exploration, unmanned exploration, etc.	At least once before baseline press-fit + as appropriate		(Secondary)(*)	(Secondary)(*)	(Secondary)(*)
		sediment	Manned exploration, unmanned exploration, etc.			(Secondary)(*)	(Secondary)(*)	(Secondary)(*)
		(air) bubble (esp. in a liquid)	acoustic survey			(Secondary)(*)	(Secondary)(*)	(Secondary)(*)
		isotope	Detection of CO_2 at the origin of the press-in.			(Secondary)(*)	(Secondary)(*)	(Secondary)(*)
	environmental impact Groundwater to be used).		Compositional change and quantification	baseline		(Secondary)(*)	(Secondary)(*)	(Secondary)(*)

Items to be carried out as primary monitoring. 0: Implemented, △: Implemented in some cases. ● and ▲ are priority monitoring items. Items marked with no mark are not implemented as long as the monitoring situation is normal.

* Only items corresponding to the risk are carried out during the transition to secondary monitoring. Baseline: to be carried out at least once before the start of injection, and the start of acquisition as appropriate.

** Reference data is obtained at the end of the process.

Source: prepared with reference to the 9th Sub-Committee on Ideal Monitoring for Future CCS Social Implementation 2024208.

1 Temperature and Pressure Measurement Technology

[Temperature and Pressure].

Back Ground

What is the relationship between the condition of carbon dioxide (CO_2), temperature and pressure?

One of the most fundamental monitoring tasks for ensuring that CO_2 is being safely injected into the reservoir as planned is temperature and pressure measurement. By monitoring the values and changes in temperature and pressure, it is possible to control the injection process, check the behavior of the injected CO_2, the properties of the reservoir and the integrity of the injection well.

In CCS, CO_2 is generally injected into the reservoir in a 'supercritical' state. In the supercritical state, the volume of CO_2 is sufficiently small, has low viscosity and is easily diffused. Injecting in this state makes effective use of the reservoir and enables effective injection. Since the temperature and pressure in the ground increase with depth, the injection is carried out into formations deeper than the depth at which the supercritical state is reached.

The injection well consists of outer multi-stage casing pipes and an inner tubing pipe, and the annular gap between the casing and tubing or casing and casing is called the "annulus". The space between the casing and the formation is filled with cement and the CO_2 is injected through the tubing into the reservoir.

The pressure in the annulus can be used to evaluate the integrity of the injection well and detect CO_2 leakage. For example, injection wells are designed to withstand pressure and corrosion, but if a hole were to form in the casing or tubing, an abnormal pressure change in the annulus would indicate a problem.

When injection is stopped, the reservoir pressure changes, and data indicating reservoir characteristics and reservoir extent can be obtained from these time-dependent changes. Additionally, during injection, confirming that the pressure is maintained at a level that does not cause the cap rock to fail is an important role of pressure monitoring.

Temperature and pressure can be measured continuously. Unplanned behavior is often associated with changes in temperature and pressure, making temperature and pressure measurements extremely important for monitoring.

Technology

Use of sensors and fibre optics in CCS

Sensors with different measurement methods are used in a wide range of industries, including the oil and gas industry and geothermal development, and can also be used in CCS. In CCS in particular, sensors installed at the bottom of the well (near the outlet) require not only accuracy but also long-term trouble-free stability. In recent years, the development of technology for temperature and pressure measurement using fiber optics, which also offers excellent long-term stability, has been promoted.

CCS temperature and pressure monitoring is conducted at least at the wellhead and at the bottom of the injection well. In addition, monitoring of the annulus section is also important..

The results of these measurements are used to check what properties of the injected CO_2 are maintained and whether it is securely contained within the reservoir. The measurement results can also be used as data to determine the properties and extent of the reservoir.

Examples of sensors that can be used in CCS include those on the right.

1. resistance thermometer sensors
2. thermistors
3. fibre-optic thermometers
4. semiconductor pressure sensors
5. quartz pressure sensors
6. fibre-optic pressure gauges

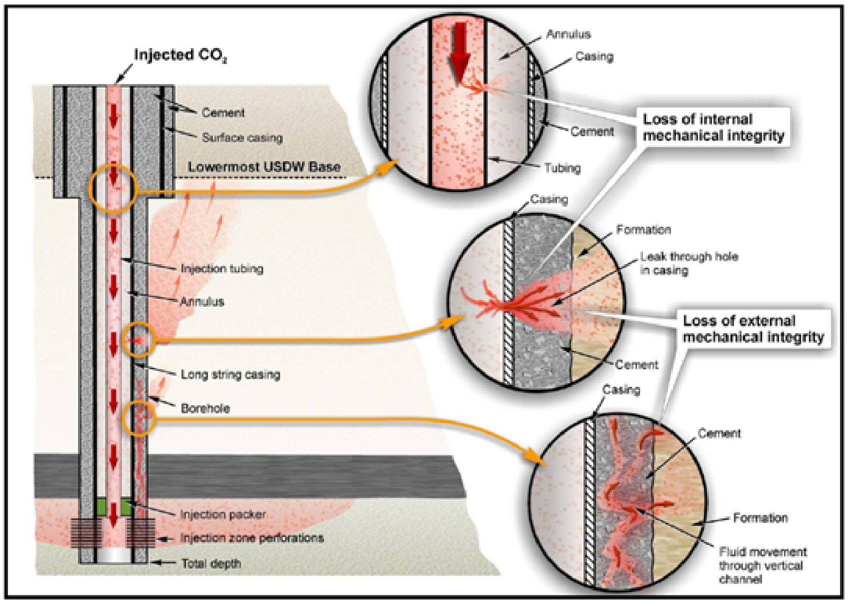
Case study Tomakomai CCS Demonstration Test

Temperature and pressure measurements were carried out at the wellhead and bottom of the injection well and at the bottom of the observation well

Data was continuously monitored and recorded by PT sensors (temperature and pressure gauges installed near the reservoir in the wellbore), and the temperature and pressure were constantly checked in order that they did not deviate from a pre-determined range during injection. As a result, the maximum pressure value was sufficiently lower than the upper limit established to avoid cap rock breakdown, and the temperature and pressure of the PT sensors were within normal limits after the start of injection. In the Tomakomai Project, the annulus pressure was measured near the wellhead apparatus (close to ground level), and together with the temperature and pressure values at the bottom of the well, confirmed the integrity of the wellbore.

In addition, during the Hokkaido Eastern Iburi Earthquake (6 September 2018), the absence of abnormal reservoir temperature and pressure trends helped determine that there was no CO_2 leakage*.

*For more information, see the study report on the effects of the Hokkaido Iburi Earthquake on CO_2 reservoirs, etc., on the Japan CCS Research Corporation website.



The necessity of annulus pressure measurement

The figure on the left shows an example of CO_2 leaking into the formation due to damage to an injection well. By installing a sensor in the annulus and measuring the pressure, it is possible to detect impairment of the integrity of the injection well. The first example at the top of the figure shows a hole in the tubing, and the second example shows a hole in the casing.

Such damage will manifest itself as changes in annulus pressure. Whether the pressure increases or decreases depends on the relationship between the formation pressure, annulus pressure, and tubing pressure, as well as the location of the damage. However, by detecting pressure changes and conducting further investigations, it is possible to identify the cause and implement countermeasures.

Note that even if there is no damage, the heat from fluids flowing through the pipe during operations can conduct into the annulus, causing the annulus fluid to expand and result in an increase in annulus pressure.

Figure from: EPA, "Geologic Sequestration of Prepared with reference to 'Carbon Dioxide Underground Injection Control (UIC) Programme Class Six Well Testing and Monitoring Guidance' (2013).

Advantage 1: Monitoring temperature and pressure is essential for safe operations, and is required by law in many countries. It also provides data that is extremely useful for improving social acceptance.
Advantage 2: Temperature and Pressure data is used to improve the accuracy of reservoir models required for the long-term management of projects.
Advantage 3: Fibre optic technology is expected to save labour and reduce costs.

2 Micro-Seismicity Measurments

[Micro-Seismicity]

Back Ground

High level of interest in monitoring in earthquake-prone Japan for the management of CO_2 injection

Minute seismic activity is monitored by highly sensitive measuring equipment. Continuous monitoring provides important data showing that there is no link between the surrounding seismic activity and CO_2 storage.

In Japan, where earthquakes are common, there is a high level of interest on whether earthquakes are induced by CCS projects and whether natural earthquakes have any effect on the reservoir. The monitoring of perceptible earthquakes as well as tremors that cannot be felt by humans is important. Detailed monitoring and recording of seismicity, including micro-seismicity, is effective in explaining, for example, that there is no relationship between natural earthquakes and CO_2 injection.

Technology

Methods for detecting very small seismicity

Seismometers are devices that convert ground movements into electrical signals and measure them. High-sensitivity seismometers and other equipment are used to measure and monitor the amplitude and period in three directions (east-west / north-south / up-down). Common products can be used for the equipment, but there are also devices that can be installed on the seabed or in the wellbore. Seismometers for use on the seabed include ocean bottom seismometers (OBS) and ocean bottom cables (OBC).

It is also possible to refer to data from existing seismic networks set up by the Japan Meteorological Agency and others.

Furthermore, the Research Institute of Innovative Technology for the Earth (RITE) is developing a CO_2 injection management system (ATLS) that can comprehensively monitor various observation data including micro-seismicity observations and injection conditions with a view towards the commercialization of CCS. It is expected that this system will enable necessary measures to be taken as soon as possible in the unlikely event that abnormal conditions are observed.

Case study　Tomakomai CCS Demonstration Project

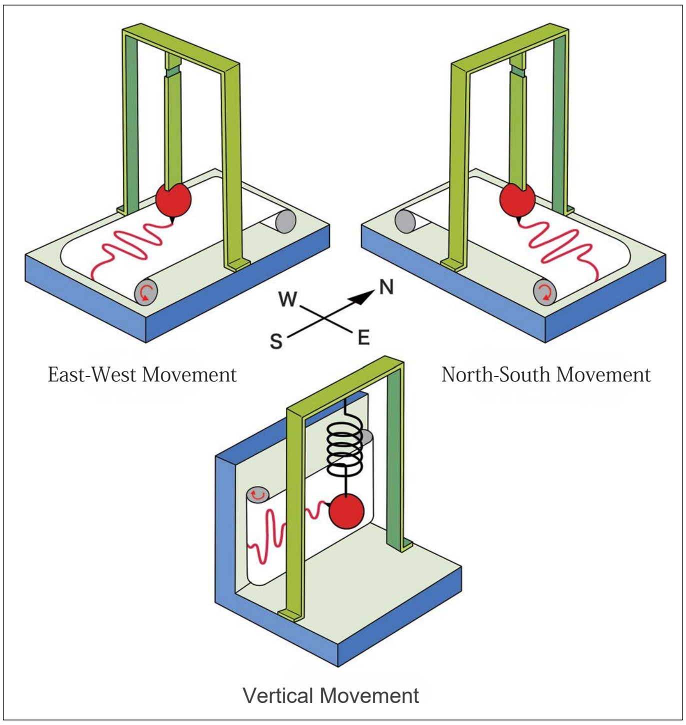
An onshore seismometer, borehole seismometers, ocean bottom seismometers and an ocean bottom cable were installed to monitor seismic activity and micro-seismicity near the injection sites.

Specifically, we installed observation wells, an ocean bottom cable (OBC) equipped with 72 small seismic sensors (geophones) for seismic surveys, ocean bottom seismometers (OBS) at four offshore locations, and an onshore seismometer equivalent to the Japan Meteorological Agency's seismic observation network, and conducted micro-seismicity monitoring in the reservoir area (within a 6 km east-west by 6 km north-south range).

As a result, we confirmed that micro-seismicity undetected by the Japan Meteorological Agency's seismic observation network could be reliably detected.

A s a result of the monitoring, no micro-seismicity or perceptible earthquakes associated with CO_2 injection have been detected in the Tomakomai CCS Demonstration Project. Additionally, following a subsequent review, the onshore seismometer and OBS were removed after injection cessation, as it was determined that their removal would not affect the positioning accuracy of micro-seismicity if the other seismometers were available.

Since the Tomakomai Project was a demonstration project, we established a monitoring network with multiple instruments and locations to collect data over a wider area. In future CCS projects, it will be necessary to select appropriate instruments and locations based on the site conditions.



Microvibrometer

In general, seismic observations are recorded by seismometers, which convert ground movement into electrical signals in three components: east-west, north-south and up-down movements. Vibrometers are a type of seismometer, and microvibrometers use acceleration sensors to record acceleration in the three components (XYZ) of three-dimensional space. There are several types of accelerometers, but servo types are mainly used for seismic observations involving micro-seismicity, as they are capable of high-precision measurements.

Source: prepared with reference to the website of the National Research Institute for Earth Science and Disaster Resilience

point

Advantage: Micro-seismicity measurement serves as scientific "explanatory material" to show that the CCS is not triggering earthquakes.

Issue : Micro-seismicity occurs due to various causes, including earthquake activity, transportation, construction sites, coastal waves, and volcanic activity. Most micro-seismicity does not immediately affect daily life, but the acceptable level varies depending on the characteristics of the area and the continuity and public nature of the project, so it is necessary to consider how to deal with micro-seismicity on a project-by-project basis.

3 Optical-Fibre Measurement Technology

[Monitoring of CO_2 behaviour] [Monitoring of well integrity] [Confirmation of well integrity]

Back Ground — Using optical fibres as sensors

Optical fibers are widely used not only for data transmission but also as sensors. They are characterized by their ability to continuously measure at multiple points over long sections. The ability to capture strain and vibration makes this technology indispensable for quickly detecting damage and defects in bridges, tunnels and plant equipment.

In the field of CCS, it is increasingly attracting attention as a monitoring technology in the vicinity of wells. The objective is to continuously measure the temperature, strain and vibration of the formation along the wellbore in time and space to monitor whether the CO_2 injection is being operated safely. Specifically, for example, it can determine how much force is being applied to the injection well by the injection of CO_2 and whether CO_2 is leaking along the injection well.

Technology — Multi-measurement of temperature, strain anvibration

Fiber-optic measurements utilize the different scattering light properties that occur when light passes through a fiber. Temperature, strain and vibration can thereby be measured.

● **Temperature :**
Optical fibers detect temperature changes, which help monitor whether CO_2 is leaking along the borehole.

● **Strain :**
Pressure changes in the reservoir/cap rock are monitored by measuring changes in strain.

● **Vibration :**
By analyzing vibrations, it is possible to observe micro-seismicity near boreholes. In recent years, optical fibers have also been used in DAS-VSP (see P23) for seismic surveys and is useful for understanding the distribution of CO_2 near boreholes.

The advantages of optical fiber technology are as follows:

· Continuous data acquisition
The entire optical fiber becomes a sensor, allowing continuous data to be taken in time and space.

·Long-term use (20 years or more) is possible
By installing properly protected fiber optic cables from the outset, there is no need for maintenance or calibration, and data can be retrieved at any time. This significantly reduces operating and running costs.

·Can be used as a multi-sensor.
Installing a single fibre-optic cable bundling several optical fibres together allows three types of data to be acquired at once.

This is significantly less expensive than installing individual sensors.

Issues and prospects

Optical fiber measurement technology is at a practical stage in oil field development because it can collect data for multiple purposes. It may replace some existing measurement equipment in CCS in the future, but there are various issues to be resolved before it can be put into practical use, such as accuracy and durability. For example, attempting to overcome its weakness against bending results in increased weight, rendering measurement impossible. To address this, the Research Institute of Innovative Technology for the Earth (RITE) developed the world's first optical fiber cable that can be bent significantly along with a protective tube, thereby overcoming this drawback. Further technological advancements are anticipated, with expectations for accelerated practical implementation in the future.

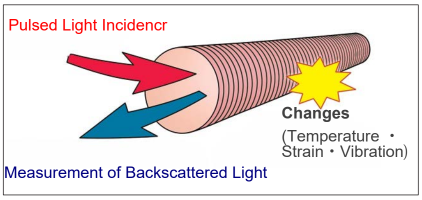
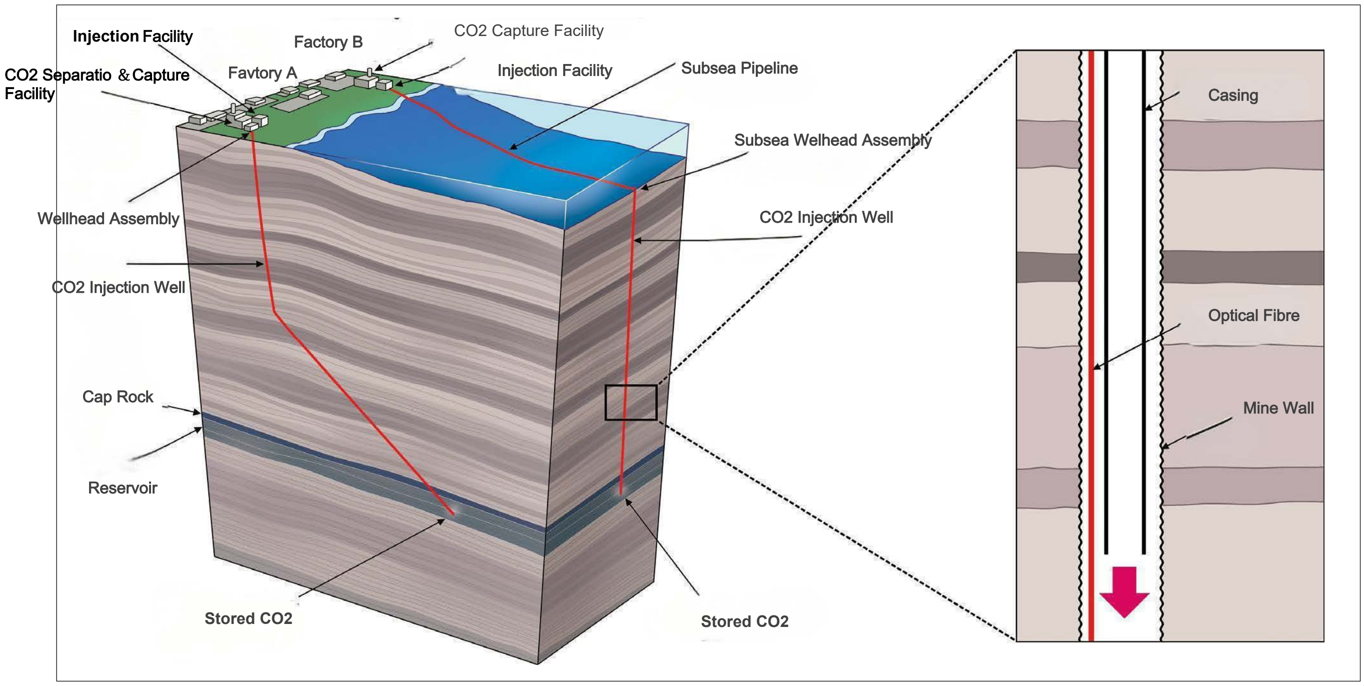


Image of fibre-optic measurement Ⅰ.

Optical fiber measurements utilize the scattered light generated by changes in the optical fiber. The strands of an optical fiber consist of a core with a high refractive index surrounded by a cladding layer with a lower refractive index. Laser light pulses incident on the core are scattered inside the fiber. There are three different types of scattered light with different properties, each of which can be used to measure changes in temperature, strain, etc. Source: prepared with reference to RITE CCS Technical Workshop 2013 document 'On the development of technology for observing the formation stability of CO_2 injection sites using optical fibers'.



● **Image of measurement using fibre optics** II.

Optical fibres are pre-installed along the wellbore wall deep underground to observe temperature, strain, etc. Source: prepared with reference to images, etc. from the website of Japan CCS Co., Ltd.

4 Logging Technology

[Monitoring of CO_2 behaviour] [Leakage monitoring].

[Confirmation of well integrity].

Background — Accurately assessing the situation around the wellbore

CCS sites have wells for investigating the subsurface, for injecting CO_2 and for observation (monitoring), and these are called wells. Well logging is the process of lowering various devices into these wells to investigate the distribution of CO_2 and the surrounding strata.

The area examined is limited to a horizontal radius of a few meters from the well center, but various data can be taken at intervals of several tens of centimeters along the wellbore. In addition, the behavior of the surrounding area, including the formation and the wellbore itself, due to the injected CO_2 can also be investigated in detail.

Technology — Various logging technologies

In well logging, various measuring instruments can be moved up and down in the wellbore to determine formation features at intervals of several tens of centimeters along the wellbore in the direction of depth. This allows the characteristics of the formation (e.g. differences between reservoirs and cap rocks) to be determined. In addition, repeated data acquisition can be used to track changes in the formation's elastic wave velocity, resistivity, etc. over time.

The purpose of well logging in CCS monitoring is to track changes over time by repeatedly obtaining data. Specifically, long-term changes are investigated using logging equipment installed around the reservoir to check whether the CO_2 injected into the reservoir is properly trapped in the reservoir and whether there is any leakage to other parts of the reservoir, and whether there are any abnormalities in the wellbore itself.

● Velocity logging

The injection of CO2 into a formation causes a decrease in its elastic wave velocity. By measuring this, the distribution of the CO2 can be tracked. Velocity logging is conducted by emitting and receiving signals between devices, obtaining the elastic velocity (P-wave and S-wave) of the formation.

VSP (Vertical Seismic Profiling) logging

Seismic waves emitted from a seismic source on the surface are recorded by a receiver in the wellbore to determine the state of the formations around yhe wellbore and CO_2 storage.

Cement bond logging

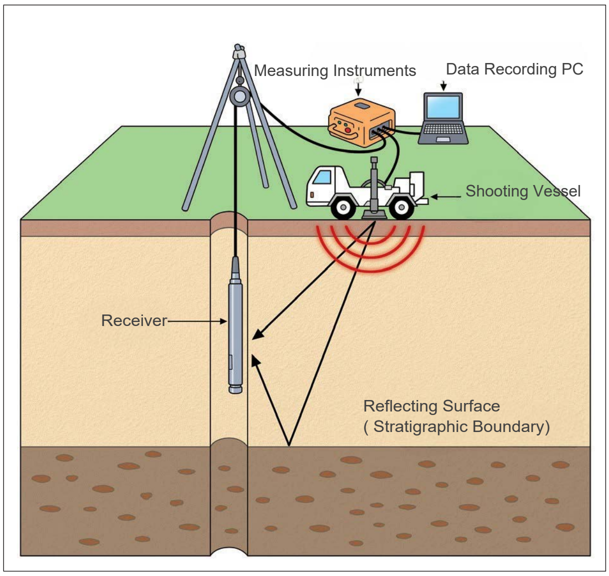
The cement behind casing is checked to see if a CO_2 leakage path has been created.

● **Neutron logging**

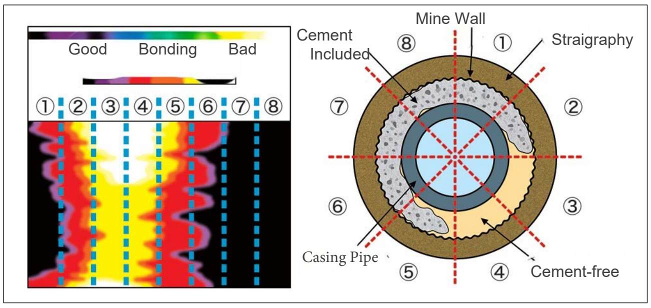
The radiation source is used to estimate how much porosity there is in the reservoir.

● **Resistivity logging**

This logging measures the resistivity (property of a material that resists the flow of electrical current) of the formation. The method used depends on the characteristics of the formation and the purpose of the inspection, but since the resistivity value changes depending on CO_2 movement, it is used to track CO_2 behavior.



Seismic waves emitted from a seismic source on the surface are recorded by a receiver located in the wellbore to determine conditions of the formation around the wellbore and CO_2 storage.
Source: prepared with reference to the website of NC Geophysical Survey Co., Ltd.



● **Cement bond logging**

This technology evaluates cementing conditions by continuously measuring the amplitude of the first wave of sound waves propagating through the casing and processing the data, based on the fact that sound waves propagate differently depending on whether there is cement around the casing or not. The left figure shows the cementing situation obtained from the measurement results, while the right figure shows a cross-sectional view of the wellbore.

Source: prepared with reference to the website of Geophysical Surveying Co., Ltd.

Case Study

Although there are no examples of implementation in the Tomakomai CCS Demonstration Project, the well logging survey items introduced here will be used differently depending on the purpose of the monitoring, the type of well (research well or injection well) and the operating conditions (before or during injection). Although the situations in which it can be used are limited, it is one of the most effective methods for ascertaining the behavior of CO_2 immediately after injection and for quickly ascertaining the migration (if any) of CO_2 to the vicinity of the observation well.

point

Advantage : allows accurate observation of CO_2 storage conditions and wellbore integrity over time.

Issue : not suitable for surveying large areas.

5 Seismic Surveys

[Monitoring CO_2 behavior].

Back Ground — Visualizing carbon dioxide (CO_2) in geological formations

Seismic surveys are a widely used technology for investigating subsurface resources such as oil and natural gas. If the technology is applied to CCS, it can provide an overall picture of the extent of cap rocks and reservoirs. First, at the stage of surveying suitable storage sites, seismic surveys are used to confirm definitively whether the necessary conditions for CCS are met, such as whether there is a porous formation such as sandstone that can store CO_2 (reservoir), whether there is a fine-grained formation such as mudstone that overlies the reservoir (cap rock), and whether there is sufficient storage capacity for the project plan.

On the basis of this data, repeated (time-lapse) seismic surveys are carried out at the same location to compare before and after CO_2 injection. The surveys allow for temporal changes in the reservoir to be captured, such as how CO_2 is spread and distributed in the underground after CO_2 storage has started, and whether there is any risk of leakage.

Seismic surveys can be carried out both on land and at sea and are the highest resolution method of geophysical surveys over large areas. Although they are expensive, it is important to plan and carry out the survey as rationally as possible by considering the frequency of implementation, the survey area, and the combination of source and receiver.

Technology — Generating seismic waves and analyzing the reflected waves

Seismic exploration uses a vibrator vehicle (a large vehicle equipped with a seismic vibrator) to generate seismic waves on land, and an air gun (a device that fires compressed air to generate sonic pulses) from a ship to generate seismic waves at sea. The seismic waves are transmitted to the strata deep underground on land and below the seabed and are reflected at each strata boundary. By recording the reflected waves with receivers installed on the ground or at sea and analyzing the data, it is possible to visualize the structure of complex strata that are layered and deformed.

This data can be used to create a geological model of the subsurface. A geological model is a representation of the structure and properties of the subsurface on a computer and is used to predict the behavior of CO_2 underground as accurately as possible. The geological model is created by interpreting the geological structure from seismic data and utilizing a variety of other information, such as existing geological information, rock samples obtained when the wells were drilled and data on physical properties of the formations obtained from well logs. Repeated seismic surveys are carried out to update the data, thereby further improving the accuracy of the geological model.

CO_2 storage alters the characteristics of reflected seismic waves. By comparing images taken before and after CO_2 injection, it is possible to determine where CO_2 has entered the formation and where it is moving, thereby understanding its movement within the formation. By comparing this movement with simulation results, the accuracy of the CO_2 distribution can be confirmed.

There are several methods of seismic exploration, which differ in how seismic waves are generated and how reflected waves are utilized. Here, we will focus on reflection seismology, which is suitable for CCS monitoring.

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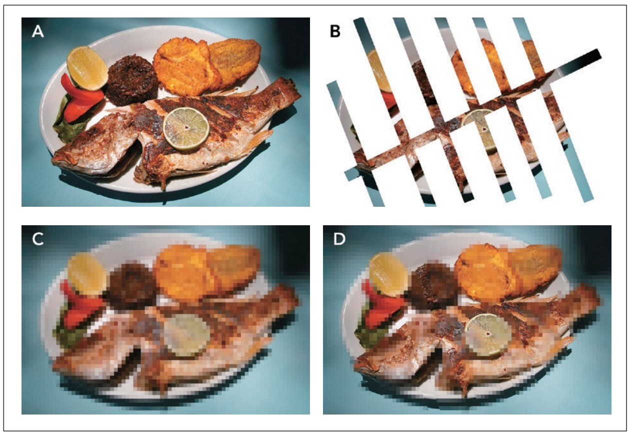
● Reflection Seismology☒

(1) 2D and 3D (two-dimensional and three-dimensional) seismic surveys

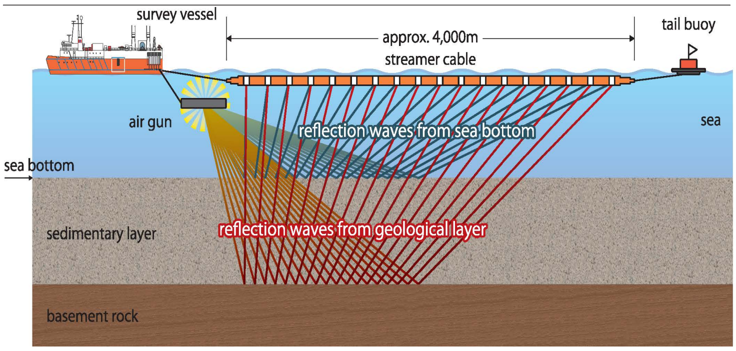
2D seismic surveys follow a straight line, called a surveys line, to obtain an image of the subsurface cross-section. Although the resolution is high, the area that can be seen is limited to just below the survey line.

3D seismic surveys use receivers placed on a plane, which allow a three-dimensional view of the subsurface. Both land and offshore areas can be surveyed, but 2D and 3D seismic surveys are currently the only methods that can be used to survey large areas of the offshore subsurface. The vessels used range from large 10,000-ton class vessels to small fishing vessels. The appropriate vessel and equipment (streamer cable, OBC, OBN) can be selected depending on the location and depth of the survey, whether it is over a large offshore area, in shallow water close to shore or in a bay where ships are passing by.



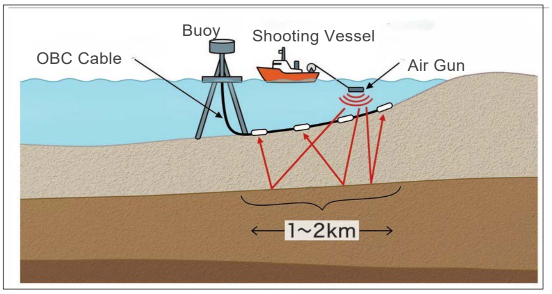
● Image of 2D/3D seismic exploration Resolts

How 2D and 3D seismic exploration can be used to understand the subsurface is illustrated using (A) an image of a fish dish. A 2D seismic survey provides high-resolution data just below the survey line, as in (B), but the area that can be seen is sparse with many gaps. On the other hand, a 3D seismic survey, as shown in (c), has a lower resolution, but the entire fish dish can be identified. Combining the results of the 3D seismic survey with those of the 2D seismic survey, a clearer image can be obtained, as shown in (D). In this way, the subsurface can be understood. Source: Rob Vestrum et al. (2008). "To Kill or to Complement: Three Technology Improvements in Foothills Seismic Imaging", RECORDER,33(9),22-26.



● Conceptual diagram of offshore 2D/3D seismic surveys using streamer cables

2D and 3D seismic surveys are the most commonly used methods for assessing subsurface structures in marine areas. However, surveys using large vessels cannot be carried out around platforms and other structures. In addition, when repeated seismic surveys are carried out, it is difficult to accurately reproduce the survey lines at sea, so the accuracy of the survey line positions over time is low.
Source: prepared with reference to the HP of Japan CCS Co., Ltd.



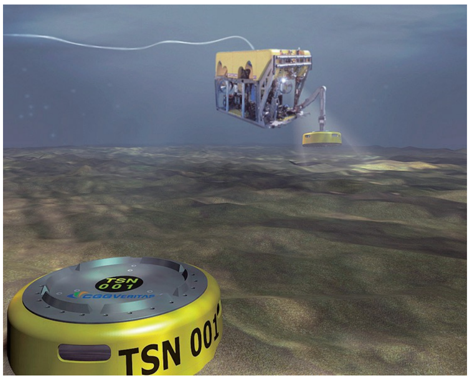
● Conceptual diagram of seismic survey using an ocean-bottom cable (OBC)

Seismic exploration using an ocean-bottom cable (OBC) involves laying a cable with a receivers attached on the seabed, capturing reflected waves from beneath the seabed and determining geological structure and rock physical properties.
Source: prepared with reference to the HP of the CO_2 Storage Group, Research Institute of Innovative Technology for the Earth (RITE)

● Image of Ocean-Bottom Node (OBN)

Seismic surveys using the Ocean-Bottom Node (OBN) involve laying a device called a 'node' with a receiver attached on the seabed to capture reflected waves from beneath the seabed. The principle is similar to an OBC, but the OBN is an independent receiver that does not require cables, allowing for a high degree of freedom in installation and the collection of highly accurate data.

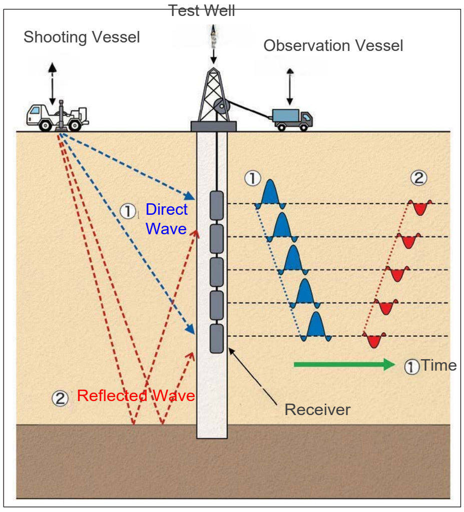
● Source: HP of Seris Tech Inc.



(2) VSP and DAS-VSP.

VSP is a method of seismic exploration that involves installing multiple receivers along a borehole. It enables the acquisition of high-quality data in the vicinity of the borehole (within a radius of tens to hundreds of meters). However, since the receivers are moved by raising and lowering them with wires during measurement, this process is time-consuming and labor-intensive. To address this, a new technology called the DAS-VSP method has been developed, which employs DAS (Distributed Acoustic Sensing: see pages 17-18) using optical fibers as in-borehole receivers.

This method significantly reduces the time required for VSP, which previously took several days, and greatly cuts down on labor and costs.



● **Conceptual diagram of VSP**

VSP (Vertical Seismic Profiling) is a wellbore-based seismic exploration method, in which seismic waves emitted from the surface of the earth or sea are recorded by a receiver installed in the wellbore. High-resolution images of the area around the wellbore (usually a cone-shaped area with a radius of tens to hundreds of meters) can be obtained. There have been disadvantages such as the complexity of data analysis and the time required to raise and lower the receiver in the wellbore, but in recent years the DAS-VSP method has been developed using a DAS as the receiver, significantly reducing the time and cost. Source: prepared with reference to the website of JGI, Inc.

● **Cross-well seismic tomography**

Cross-well seismic tomography is a method using multiple wells, installing a source in one well and a receiver in another well, and recording seismic waves traveling the subsurface. When CO2 replaces formation water, it causes a decrease in the velocity of seismic waves traveling through the formation.

At the Nagaoka CCS Pilot-Scale Test Site, this method was successfully used to delineate the CO2 distribution. Compared with VSP technology, it is easier to determine the distribution of CO2; however, in order to implement this technology, there must be multiple wells close to each other.

Case study — Tomakomai CCS-Demonstration Project

2D and 3D seismic surveys using OBCs were conducted alternately every other year before, during and after CO_2 injection. Although repeated 3D seismic surveys are ideal to accurately determine the state of CO_2 the ground, they were alternated with 2D seismic surveys due to the cost and duration of the work.

A total of four repeated seismic surveys were carried out from the start of injection in April 2016 to the end of FY 2019 to investigate the CO_2 distribution area. The distribution of CO_2 in the Moebetsu formation was detected from FY 2017 onwards, and it has been confirmed that the injected CO_2 has remained in the reservoir as expected, and that no abnormalities, such as leakage outside the reservoir have occurred.

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Advantages and Issues of Seismic Survey Technology

Advantage 1: It is a proven technology in oil and gas fields and is the most effective geophysical technology for CCS.

Advantage 2: It enables viewing the condition of the formation and CO_2 as 3D images.

Advantage 3: Comparison with simulations can confirm the certainty of the CO_2 distribution situation.

Issue 1: It is important to consider the cost implications for the CCS project as a whole and to reasonably incorporate seismic surveys into the monitoring plan. In particular, it is essential that the frequency of implementation is determined based on the progress of the project.

Issue 2: When conducting seismic surveys, it is necessary to consider the impact on users of ports and sea areas. When towing cables from the stern of a vessel or installing cables on the seabed, it may be necessary to coordinate with navigation of other vessels and fishing activities.

6 Measurement technologies based on gravity and electrical/electromagnetic surveys.

[Monitoring CO_2 behavior].

Background. A rapid, large-scale geophysical survey method for investigating the subsurface.

For CCS projects, it is very important to confirm that the injected CO_2 is retained in the reservoir area, and a number of monitoring methods are being considered to confirm this. Seismic surveys are mainly used to monitor the behavior of CO_2 and to investigate the overall picture of the reservoirs and cap rocks, but the complementary use of other methods such as gravity, electrical and electromagnetic surveys are also expected.

Gravity surveys are used as a preliminary survey method prior to seismic surveys and drilling, for example to identify geological structures where oil and natural gas is expected to be present, and also to capture minute gravity changes caused by magma movement in volcanoes. Electrical prospecting is widely used in groundwater and dam surveys, while electromagnetic prospecting is used in geothermal development.

Technology Measuring with gravity, electricity and electromagnetic waves

Slight changes in gravity (density) or electrical resistance (resistivity) values caused by CO_2 injected into the reservoir are observed and evaluated to determine the status of CO_2 in the reservoir.

● Gravity surves (Precision gravity surveys)

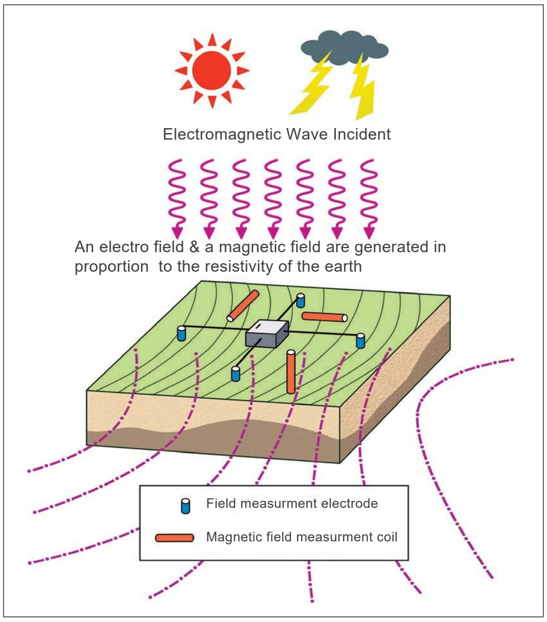
Different densities of materials in the subsurface result in different values of gravity. For example, if the water originally in the formation is 1 g per ml and the CO_2 that displaces the water is 0.6 g per ml, the value of gravity will decrease slightly before and after injection. By measuring this slight change in density, it is possible to determine where the CO_2 is stored. Precision gravity surveys are more accurate than conventional gravity surveys but are not suitable for surveys over large areas because the equipment is difficult to handle and carry. Gravity surveys have a lower resolution than seismic surveys, but they have advantages in that they can be used for continuous observation in a fixed location and are low cost.

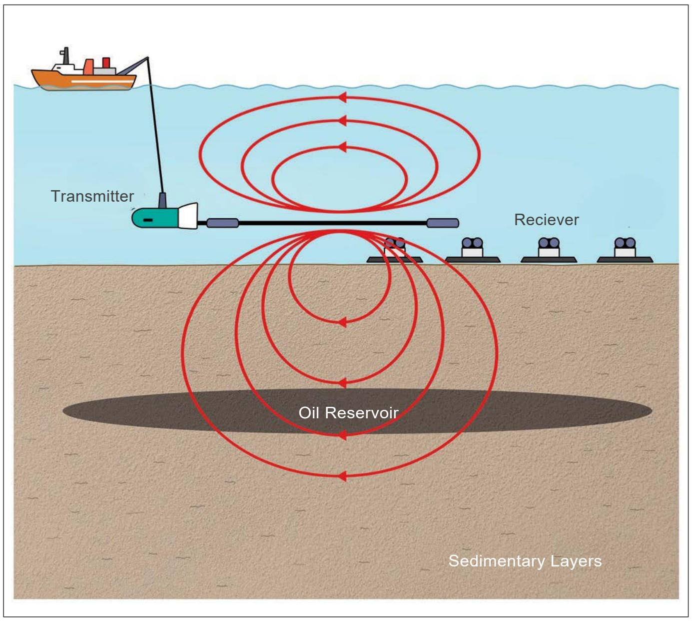
● Electrical Surveys , Electromagnetic Survey☒

Electrical surveys and electromagnetic surveys utilize signals that differ from each other, but both take advantage of changes in the electrical resistance (resistivity) of geological layers caused by CO_2. The prospecting depth is generally around 1,000 meters. Compared with seismic surveys, it is a low-cost prospecting method, but the resolution of the data obtained is low, similar to gravity prospecting.

Electrical surveys involve installing multiple electrodes on the ground surface or underground, applying a current, and measuring the potential. Electromagnetic surveys use electromagnetic waves, with methods including those that utilize natural electromagnetic signals (MT method) and those that use artificial electromagnetic signals (CSEM method).

A major feature of electrical and electromagnetic surveys is that they can observe gas saturation with high sensitivity, which is not possible with seismic surveys. However, it is not possible to distinguish whether the gas is CO_2 or another gas, so when utilized for CCS in depleted gas fields, a lot of analysis is required, including comparison with records before CO_2 injection and analysis of gas composition.





● **Schematic diagram of the MT method electromagnetic survey on land**

Electromagnetic surveys probe changes in the electrical resistance (resistivity) of a formation due to CO_2 injection; the MT (Magneto-Telluric) method measures the ratio of the intensity of the electric and magnetic fields induced in the ground by natural electromagnetic signals radiated at the surface and estimates the subsurface resistivity distribution. No signal source is required, but it is sensitive to noise. Source: prepared with reference to Takeyuki Neki, "Examination of the three dimensional analysis technology in the magnetotelluric method", Journal of the Society of Petroleum Engineers of Japan, Vol. 68, No. 1 (2003).

● **Schematic diagram of marine CSEM electromagnetic survey**

The Controlled Source Electromagnetics (CSEM) method, which uses artificial electromagnetic signals, requires a signal source but is more resistant to noise. The advantage is that the frequency can be controlled, so that the resolution can be adjusted to suit the target.
Source: prepared with reference to Japanese Association for Petroleum Technology, Petroleum Technology Handbook, Japanese Association for Petroleum Technology 80th Anniversary (2013).

Cases. Norway (Sleipner CCS Project) and Tomakomai CCS Demonstration Project

Repeated seismic surveys were carried out at Sleipner in Norway, but several supplementary gravity surveys were also carried out and detected small changes in gravity due to CO_2 injection. At the Tomakomai demonstration site, a highly sensitive superconducting gravimeter was used for the survey, but it was not possible to detect gravity changes due to the large distance from the injection point and the small amount of CO_2 injection. However, the site has the advantage that it is possible to record data continuously, so the possibility of using the system will be revisited in the future.

point

Advantage 1: As a complementary tool for seismic exploration, it is expected to enable inexpensive and simple investigation of reservoir shape and temporal changes over a wide area.
Advantage 2: It is proven in other industries and is expected to be deployed in CCS.
Issue: Due to the limited survey depth and low resolution, its application to CCS is at the research stage.

7 Formation water analysis

[Formation water and groundwater properties]

Background. Examining formation water in which CO_2 is dissolved

Many of the formations suitable for storage are sedimentary layers. Sedimentary layers are formed when mud, sand and debris are carried and accumulated by flowing water, and many of the large sedimentary layers suitable for storage are formed in marine areas. The brine that accumulates in the gaps (pore spaces) in the sediments is called formation water.

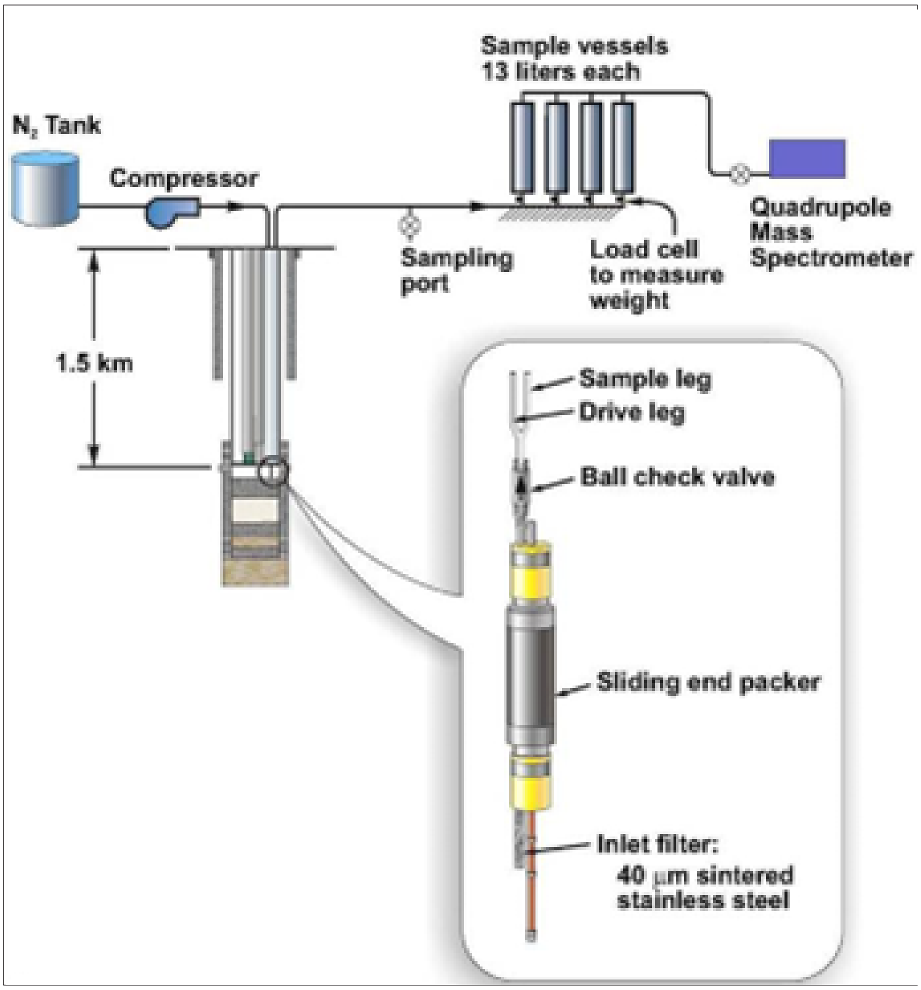
Formation water analysis examines the composition of the formation water during the baseline survey at the time of site selection, and how it changes after the start and end of CO_2 injection. Injected CO_2 enters the formation water and causes chemical changes, so analyzing the CO_2 concentration, etc. in the formation water makes it possible to trace its behavior in the reservoir. It is also possible to assess CO_2 leakage and chemical changes in the formation.

At the time of each survey, analyzing the composition of the formation water in the reservoir can tell how much CO_2 can be dissolved, how reactive it is with the rocks and whether there are pathways connecting it to the surface. Furthermore, analyzing the groundwater in shallower formations can provide a range of information, such as whether CO_2 is leaking into the shallower formations.

Technology Collecting and analyzing samples from wells

Formation water analysis involves using special equipment to collect formation water from a borehole at a specific depth within a reservoir, and then analyzing the composition and concentration of various components present in the water.

By analyzing the collected formation water, information such as carbon dioxide partial pressure (pCO_2) , hydrogen ion concentration (pH), bicarbonate ions (HCO_3) and dissolved gases can be obtained. In the case of water sampling from observation wells, changes in carbon dioxide partial pressure may also provide insights into the distribution of CO_2.



● **Schematic diagram of formation water analysis (U-tube sampling system).**

Sampling and analyzing formation fluids from the wellbore provides useful information to determine whether CO_2 is leaking at the depth of interest. However, as the solubility of CO_2 varies with pressure and temperature, sampling at great depths must be carried out in such a way that there is no significant drop in pressure or temperature when the sample is brought to the surface. The figure shows an example of the U-tube method, in which a nitrogen purge is used to isolate the collected sample.

Source: Prepared with reference to the

Underground Injection Control.
(e (UIC) Program

Class Six Well Testing and Monitoring Guidance.

Case study　Nagaoka Demonstration Tests and Overseas Examples

At the Nagaoka CCS Pilot-Scale Test Site, formation water was sampled and analyzed three times - before injection, two years and five months after the start of injection and eight years and two months after injection - in order to investigate the process of CO_2 fixation as minerals. As a result, there was a decrease in calcium ions while there was an increase in CO_2 -derived carbonic acid substances in the formation water. This suggests that calcium ions combined with carbonic acid and precipitated as calcium carbonate ($CaCO_3$) . This may indicate that the injected CO_2 is mineralizing and beginning to be fixed within the reservoir.

Overseas, formation water analysis has been carried out in CCS projects in the USA, Canada and Australia. In the USA, the Safe Drinking Water Act regulations also require regular monitoring in formations shallower than the confining layer (cap rock) to ensure that groundwater quality has not been altered by CCS.

point

Advantage 1: Analysis of the composition of formation water provides information on the state of storage and CO_2 saturation.

Advantage 2: Analysis of groundwater in shallow layers can confirm that CO_2 is not migrating towards the surface.

Issue.　: special techniques are required to collect water samples while preserving the deep subsurface environment.

8 Ground surface deformation mesurements

Background — Subsurface pressure changes are transmitted to the surface

Just as over-pumping of groundwater causes land subsidence, too much CO_2 injection can cause the ground to gradually rise. Such changes in the ground surface are monitored by surface deformation measurement. This monitoring can confirm whether the amount of CO_2 injection is appropriate, whether the injected carbon dioxide is properly contained in the reservoir and whether it has moved outside the expected range.

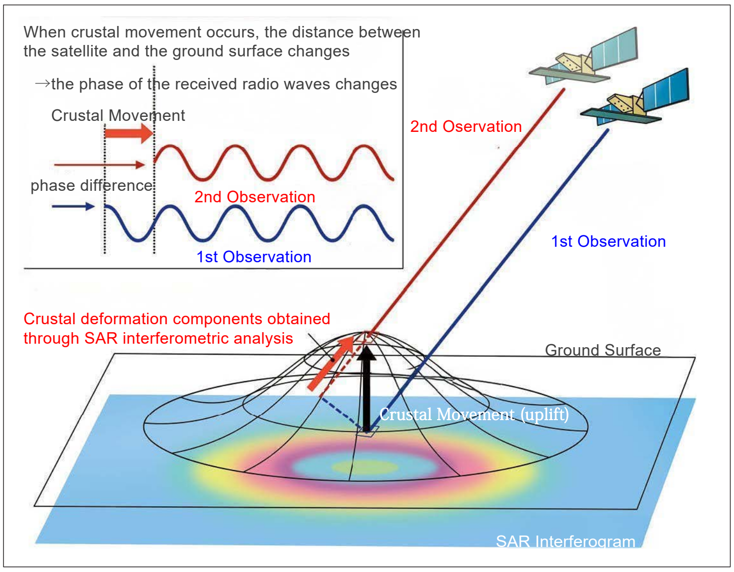
Note that changes cannot be measured in CCS over marine areas, making it difficult to apply.

Technology — Use of remote sensing technology

Although levelling (a method of measuring the difference in height between two points using levelling equipment) has traditionally been used to capture ground surface deformation, remote sensing technology using satellite data is recently being utilized. This section introduces InSAR (Interferometric Synthetic Aperture Radar) and other measurement techniques using inclinometers and GPS.

● InSAR.

This technology monitors changes on the Earth's surface from space, allowing us to observe the Earth's surface in a visible form using satellite images. It is also used to investigate areas of uplift and subsidence caused by earthquakes triggered by active faults. Satellites orbit the Earth, repeatedly emitting microwaves, which are then received and the data synthesized to capture changes in the shape and elevation of the Earth's surface. This method does not require the installation of observation equipment on the ground and can detect changes over a wide area with an accuracy of several millimeters.



● **Principle of measuring surface deformation with InSAR.**

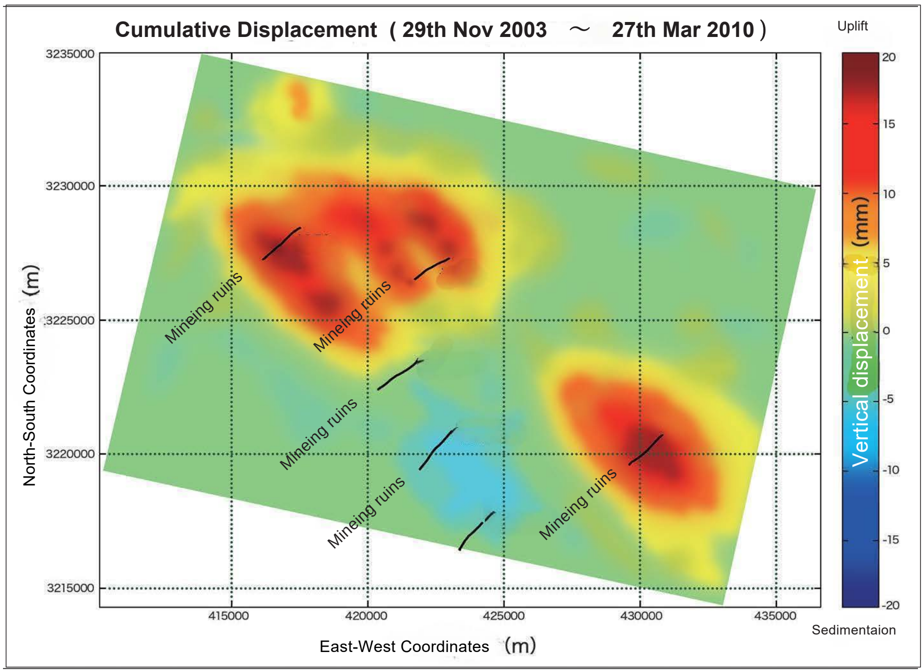
InSAR (Interferometric Synthetic Aperture Radar) is a technology that uses the 'phase' of radio waves to obtain images. Phase is a fraction of the distance between the satellite and the earth's surface (actually twice the distance as it is round trip) divided by the wavelength of the radio wave. By conducting two observations of the same location on the ground surface and taking the difference between the phase images (interferometric analysis), it is possible to obtain information on small differences in distance and to capture ground deformations. Source: prepared with reference to the website of the Geospatial Information Authority of Japan, Ministry of Land, Infrastructure, Transport and Tourism

●GPS

GPS is a satellite positioning system that is used in everyday devices such as smartphones and car navigation systems. Based on the time it takes for radio waves emitted from a satellite to reach a receiver, it is possible to measure the position on the earth's surface with an accuracy of a few centimeters. Since the data obtained by GPS is limited to the measurement point, it is used to complement measurements by InSAR and inclinometers, which cover a wide area.

Case study. Algeria (InSalah) case study

Satellite-based monitoring of surface deformation covers terrestrial areas. For example, in the case of In Salah (CCS project in Algeria), CO_2 injection increased the pressure in the reservoir, and surface uplift was observed around the injection well, which caused the injection to be stopped. Another significant achievement was the visualization of the CO_2 distribution area spreading in the direction of easy entry within the reservoir, as the spread of the uplifted area was not concentric.



● Satellite images of surface deformation due to CO_2 injection in the InSalah project.

InSAR was used for CCS monitoring in the In Salah project in Algeria. The surface of In Salah is a rocky desert with little vegetation, making it easy to see the phase differences in radio waves and suitable for observation by InSAR. The black dots in the diagram show well locations, and the black lines show the well trajectories. The red areas indicate uplift and the blue areas indicate subsidence. Data analysis over time shows that the uplift rate centered around the injection wells is up to 5 mm per year and the cumulative uplift exceeds 20 mm. Source: Mathieson et al./ In Salah CO_2 Storage JIP: CO_2 sequestration monitoring and verification technologies applied at Krechba, Algeria, Energy Procedia, v.4, pp:3596-3603.

point

Advantage 1: Remote sensing technology allows very high accuracy data to be obtained at relatively low cost.

Advantage 2: InSAR does not require the installation of any instruments or other equipment on the ground surface.

Issue: implementation in maritime areas is difficult and the scope of application is currently limited to terrestrial areas.

9 Environmental montoring.

[Environment/Marine environment]

Background. Assessing the environmental impact of CCS

As the sites where CCS is implemented are selected according to national and international standards, the risk of leakage of the contained CO_2 into the environment (biosphere) is sufficiently low. On top of this, there are cases where monitoring of environmental impacts is carried out to obtain scientific evidence to explain that the CCS project will not affect the marine environment, living organisms, etc. Specifically, this involves ascertaining whether there is any impact on the surrounding environment, residents and biosphere, as well as changes in the terrestrial and marine environment if there are concerns regarding CO_2 seepage.

Based on the data from such environmental monitoring showing that there is no concern (evidence) of seepage, it is important to explain the situation to local residents and other stakeholders in an easy-to-understand manner and gain their understanding in order to continue stable operations.

However, the environmental impacts to be targeted will vary from area to area, and the content and timing of environmental impact assessment will need to be determined in a case-by-case manner.

Technology Collecting and analyzing samples pertaining to the environment

.In marine areas, seawater and sediments from the seabed are collected and analyzed for their properties, such as CO_2 and oxygen content, pH (which varies with the amount of CO_2) , water temperature and salinity. Observations may also be made underwater, such as the presence or absence of air bubbles. On land, soil and atmospheric gases are sampled and analyzed. In addition, biota may also be surveyed.

Although CCS does not use groundwater layers used for domestic water etc. as a reservoir, water can be taken from the groundwater layer to check whether it contains CO_2 that has leaked from the reservoir, or to confirm that CO_2 has not migrated towards the surface.

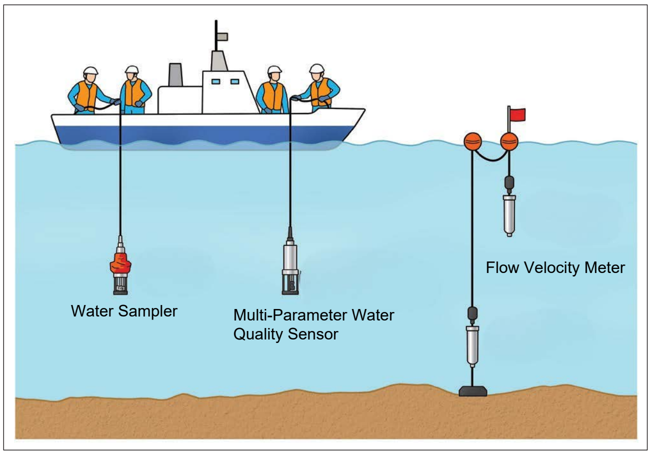
The purpose of environmental monitoring is to demonstrate that the CCS project has not affected the surrounding environment, the local population's living area and the biosphere. Although the respective techniques, such as environmental sample collection and analysis methods, are well established and widely used, the data to be obtained and the evaluation of the results obtained are not uniformly defined throughout the country, as the target of the monitoring is the natural environment.

The data obtained from environmental monitoring is also susceptible to external factors such as natural variations, for example, the concentration of CO_2 in seawater can vary depending on various factors such as season, weather, plankton blooms, ocean current conditions and water inflows from rivers.

Meanwhile, new technologies are also being developed. For example, the Research Institute of Innovative Technology for the Earth (RITE) is developing technology to distinguish between CO_2 in seawater that is naturally occurring and CO_2 that has leaked from reservoirs. It is important to consider the monitoring method, while utilizing practical, cutting-edge technologies such as these.

● Multi-paramater water quality sensor
Mulutiiple items required for water quality surveys, such as water temperature, pH, dissolved oxygen and salinity, can be measured with a single unit.

● Niskin water sampler
The container has a lid at the top and bottom, and when a weight threaded through the wire suspending the water sampler is dropped from the boat to a predetermined depth, the stopper is released and the lid is closed, allowing water sampling.



Schematic diagram of water sampling, water quality observations and tidalcurrent observations.

Water quality surveys are comprised of: (i) seawater sampling using water samplers, (ii) observations by multi- parameter water quality sensors (measuring depth, temperature, salinity, pH, etc.), and (iii) observations of the direction and velocity of tidal currents at observation points. The best accuracy of observation is achieved by analysis based on water sampling. On the other hand, a multi-parameter water quality sensor can measure the vertical distribution at multiple depths, and by comparing the data obtained by the multi-parameter water quality sensor with the water temperature of the sample taken by the water sampler, it can be checked whether the water sampling is taking place at a given depth. Observation data on flow direction and velocity can also be used to infer the location of anomalies when abnormal observations are obtained.

Source: marine environment survey report by the Marine Biological and Environmental Research Institute

(All three items. Illustrations are based on the report)

Case study

Tomakomai CCS Demonstration Project and environmental survey in Canad (Onshore)

In Tomakomai, as part of the marine environmental surveys, the water quality (dissolved oxygen concentration, CO_2 partial pressure, pH, etc.,), bubble confirmation, bottom sediment and marine organisms (zooplankton and benthic organisms) are investigated on a cycle shorter than required by law (seasonally) as it is a demonstration project. Also, onshore, CO_2 measurements are carried out in the vicinity of the wellbores.

There has been a case in onshore Canada where it was possible to compare the CO_2 of the injected CO_2 with the CO_2 of the soil gas and determine that no leakage had occurred on account of the difference in composition.

point

Advantage 1: A scientifically based explanation of the relationship between CCS projects and the surrounding environment can be provided.

Advantage 2: The results obtained are useful for adressing social concerns and the demands of the surrounding population.

Issue. : Data must be evaluated with great care as it is susceptible to external factors such as natural variations.

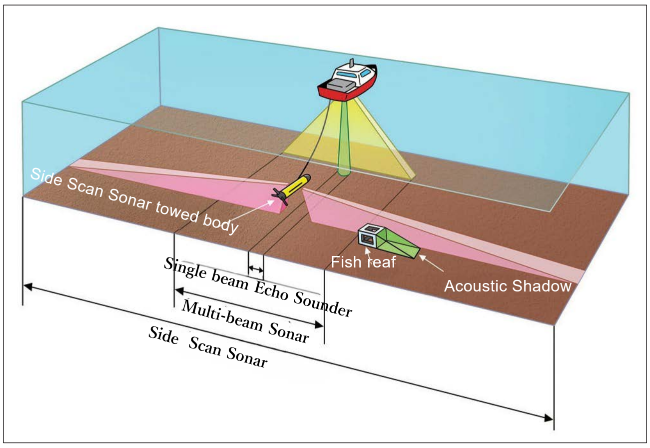
10 Acoustic Surveys
[Environment /marine environment/bubbles]

Background — Studying the topography of the seabed and air bubbles in the sea

In environmental monitoring at sea, the detection of submarine depressions and other potential CO_2 seepage pathways and repeated measurements can be used to investigate changes in the seabed topography before and after CO_2 injection. Alternatively, sound waves can be transmitted from a boat into the water and the strength of the waves can be used to check for the presence of air bubbles. Finding air bubbles is based on the same principle as fishing boats using sonar to find schools of fish.

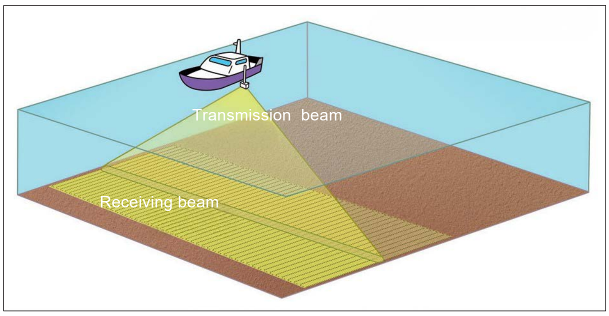
Technology — Repeated transmission and reception of sound waves from the ship

Acoustic surveys are generally used to survey the seabed by repeatedly sending and receiving sound waves as the vessel moves forward. They are mainly used to collect data for seafloor topographic mapping, with side-scan sonars (SSS) ,multi - beamecho sounders (MBES) and synthetic aperture sonars being put to practical use. It is important to select the appropriate technique depending on the size and depth of the targeted bubbles.



● Schematic diagram of side-scan sonar.
Side-scan sonar transmits sound waves in a fan shape from transducers attached to both sides of a towed vehicle moving in the sea. The sound waves that hit the seabed surface return in order of distance, and the intensity of these sound waves is recorded over time. By analyzsng the data obtained, a two-dimensional image of the differences in scattering intensity on the seabed surface can be created. Although it is not possible to measure the depth of the water, a three-dimensional image can be created by taking into account the depth data obtained by other measurement methods. Source: prepared with reference to the website of Hydro System Development Inc.

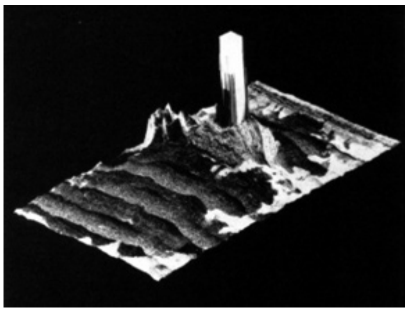
Conceptual Diagram of the Mills Cross Method



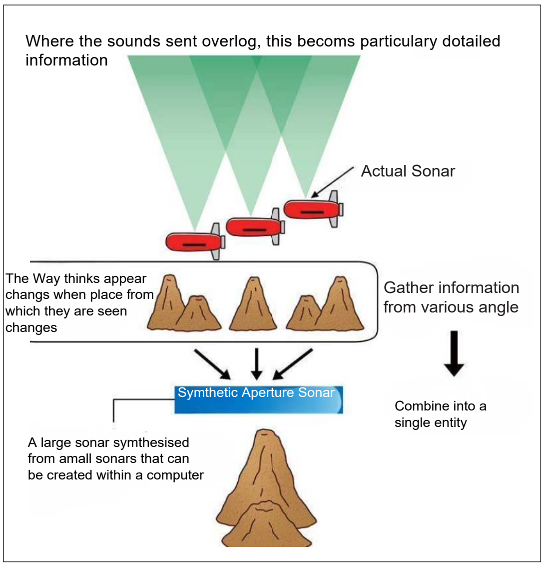
Schematic diagram of multi-beam echo sounder (MBES)
Multi-beam echo sounder (MBES) transmits sound waves from a multibeam sounding instrument in a fan shape, which is broad in the port and starboard directions and narrow in the fore and aft directions of the survey vessel. It measures the two-way travel times of the sound waves reflecting off the seabed, and can measure the depths of many points, enabling the creation of a three-dimensional image. The technology enables detailed topographical changes on the seabed to be determined.
Source: prepared with reference to the website of Coastal Ocean Research Co., Ltd.

● Three-dimensional display of side-scan image

Source: Toshiaki Ueki, "Delineation of seabed by side-scan sonar" (1990; in Japanese)



As acoustic devices (sound waves) are used to detect bubbles caused by methane and other substances in the sea, development is underway of a method for detecting CO_2 bubbles using side-scan sonar, which is capable of wide-area bubble detection. However, compared to methane, CO_2 is more easily dissolved in seawater, making it difficult to detect, and research is ongoing to determine the conditions under which it can be detected.



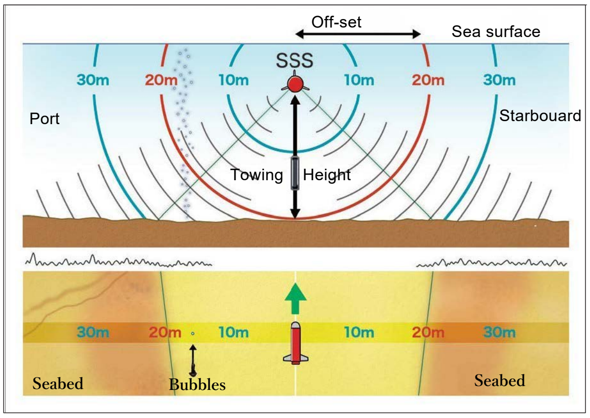
● **Conceptual diagram of synthetic aperture sonar.**
Synthetic aperture sonar is a sound wave transmitting device developed based on the side-scan sonar. By processing the seabed reflection information obtained at numerous different positions while moving with a computer, the resolution and sensitivity can be significantly improved.

Source: HP of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

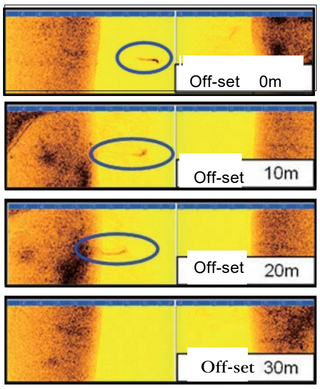
Case study — Demonstrations at sea

In 2017, the Research Institute of Innovative Technology for the Earth (RITE) conducted a demonstration test in which CO_2 bubbles were released from the seabed and observed with side-scan sonar in waters at about the same depth as offshore Tomakomai (approximately 30 m). As a result of measurements while changing the bubble release rate, bubble size and observation conditions, it was found that bubbles could be detected at a ship speed of 2.5～ 5.5 knots and a release (seepage) rate of 500～ 5000 ml/min, but as the detection accuracy decreases the further away from the bubbles, there are issues such as the efficiency of the survey.

Furthermore, even if bubbles are found, the type and origin of the gas cannot be determined. In order to determine whether the bubbles are related to CO_2 leaked from the reservoir, it is necessary to collect the bubbles and analyze them separately.



● **Principle of bubble detection by side-scan sonar.**
Side-scan sonar is a device that emits sound waves in both port and starboard directions of the device and receives the reflected waves to obtain images of underwater objects and the unevenness of the seabed. The device is submerged in the sea and towed by a ship to detect CO_2 bubbles in the sea.



● **Detected CO_2 bubble image**

CO_2 bubble image obtained in RITE's 2017 demonstration test. Source: HP of the Research Institute of Innovative Technology for the Earth (both diagrams). Illustrations on the left were created with reference to the HP.

point

Advantage 1: The formation of air bubbles can be seen in easy-to-understand images.

Advantage 2: Time-staggered observations at the same location make it easy to distinguish between fish shadows and bubbles.

Advantage 3: The topography and topographic changes of the seabed can also be studied.

Issue : Bubble detection technology has not yet reached a mature stage, and caution is required, such as using other methods in combination. However, some research institutions in Australia are conducting full-blown research on this monitoring method considering it to be very promising.

11 Simulation

[Monitoring of CO_2 behaviour].

Background "Checking the answers" between observed data and calculated results

Simulation is not a monitoring technology, but an overview of it is presented here for the convenience of the users of this booklet. Simulation is a technology to predict the future (e.g. after 1000 years) by creating a numerical model of the subsurface of the target storage area (reservoir model). In CCS, it is necessary to show whether the CO_2 injected into the ground is stored stably in the geological formation. For this reason, at the project planning stage, CCS first examines the structure and characteristics of the subsurface, models the subsurface geology, calculates how much CO_2 can be stored there and how this CO_2 will move in the subsurface, and selects a location where it can be stored stably even after 1,000 years (CO_2 storage simulation at the suitable storage site investigation stage). Based on the preliminary survey of suitable storage sites, a project plan is drawn up and the actual project is launched.

The model created during the suitable storage site investigation phase can be considered an initial model. After drilling injection wells and observation wells and commencing CO_2 injection, the model is updated based on various additional observation results obtained through monitoring (simulation during the operational phase). In this way, by comparing observation results with simulation results, the model is revised and the simulation is updated, as if 'checking the answers'. This is considered a critical enabling technology for making various 'decisions' and 'judgments' when planning CCS projects or considering future trends. By continuously improving the model's accuracy through the dual approach of monitoring and simulation, we confirm the long term stability of CO_2 storage and proceed with the project.

Technology Creating models and repeating updates

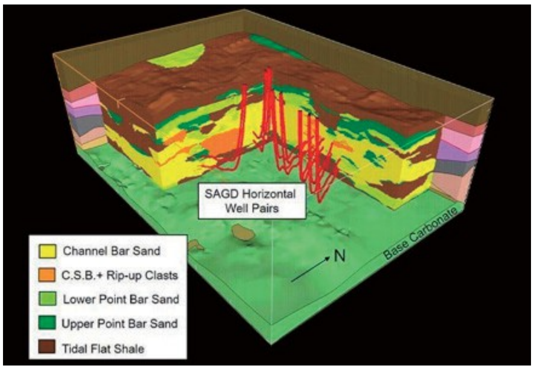
CCS involves simulating how the subsurface changes with the injection of CO_2 and looking ahead to after the injection has been completed (e.g. 10, 100 or 1000 years later). The process is divided into the following three stages

(1) Creation and updating of reservoir models.

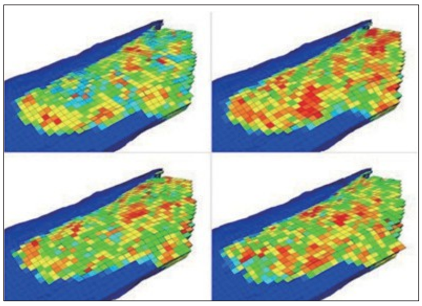
Accurate prediction of CO_2 movement requires the creation of highly accurate models. Us ing information obtained from seismic wave exploration, such as the thickness and extent of the reservoir, and from various monitoring methods, such as the proportion of rock pores and fluid flowability, a geological model is created using computers. The reservoir model, which simulates how CO_2 is stored within the reservoir, can be considered a simplified version of the geological model.

● Creating/updating reservoir models

A geological model is created based on geological information and observation data (e.g. porosity and permeability distribution, geological structure, thermal properties for rock types, reservoir shape and size, fluid properties) obtained from seismic surveys and wells. To simplify the calculations for analyzing the geological model and to enable calculations to be carried out in a practical amount of time, upscaling is carried out by grouping several cells together and increasing their size (making a coarse model), and the reservoir model is incorporated so that changes such as fluid movement in the reservoir can be calculated. The figure is an example of a three-dimensional geological model of a reservoir.



Example of a three-dimensional geological model of a reservoir.
Source: Takahashi, A., Kashiwabara, K., Mizobata, S., Shimada, N., Nakayama, T., Furuse, M. and Torigoe, T., 2006, Construction of a three-dimensional geological model of oil sands reservoirs, Geophysical Exploration, 593233-244.



Example of four different reservoir models
Source: HP of Japan Petroleum Exploration Co., Ltd.

(2) History matching (comparison of observed and calculated values).

History matching refers to the process of comparing calculated results with observed data and modifying the model. In CCS, the reservoir model is modified by matching the calculated results of simulations with the actual injection volumes and observations from monitoring. Repeating this history matching process and keeping the discrepancy between calculated and observed results as small as possible will minimize the discrepancy in future predictions after 1000 years.

3) Future projections

Using a model with improved accuracy through history matching, we predict the current CO_2 storage status and future movement and evaluate the presence or absence of leakage from the reservoir.

Case study Tomakomai CCS Demonstration Project

Several models were created by history matching to ensure that the downhole pressures were matched.

In all cases, the long-term future simulation predicted that the injected CO_2 would remain in an area of about 1000 m around the injection well even 1000 years after stoppage of injection.

point

Adovantage1: Models are created based on data obtained from different types of monitoring to predict the behavior of CO_2 after 1000 years. It is a key technology for decision-making in CCS projects.

Adovantage1:Improving the accuracy of the model enables more precise predictions of whether CO_2 is properly retained underground, thereby reducing the range of predictions for 1,000 years in the future. This will help ensure the safety and security of CCS projects.

Issues: The issues include creating models with the appropriate accuracy while minimizing costs and effort, as well as appropriately comparing results with simulation results and determining the frequency of model updates. Therefore, it is important to thoroughly understand the magnitude of model uncertainty through simulations conducted at the preliminary investigation stage.

12 Dealing with mechanization

[Environment/Marine environment]

Background. The usefulness of mechanization for monitoring at sea

One of the challenges for the future proliferation of CCS projects is to reduce the cost and burden of monitoring. Mechanization can be a solution to the challenges of surveying in places where humans cannot easily go, such as the deep seafloor, and for simple tasks that can be automated.

Technically, a wide range of equipment and devices have been developed and mechanization has been incorporated in a number of areas, for example, in marine surveys, dam lakes, environmental surveys in areas where thermal effluents from power stations flow out, fishing reefs, archaeological sites and searches for fallen objects. There is potential to explore the possibilities of mechanization in CCS monitoring.

Technology Different types of marine UAVs

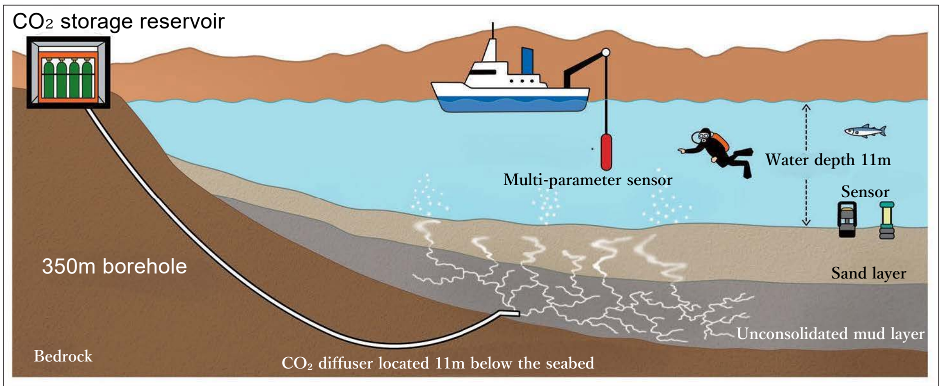
Unmanned submersibles and unmanned watercraft are used for monitoring in the ocean, and remotely operated vehicles (ROVs) have been used for CCS monitoring overseas.

Other types include autonomous unmanned vehicles (AUVs), which move fully automatically and are suitable for water quality and seabed topography surveys over large areas, autonomous unmanned surface vehicles (ASVs), also known as 'water drones', and remotely operated unmanned surface vehicles (ROSVs).

Case studies Examples of overseas CO_2 emission tests and the use of unmanned vehicles

1) Japan-UK Joint CO_2 Leakage Experiment (QICS Project)

The QICS Project is a joint research project between the UK and Japan conducted in Scotland. It was the world's first experiment to actually release CO_2 from beneath the seabed, investigating the environmental impacts and recovery processes. It was found that the environmental impact of CO_2 seepage was extremely small, and that recovery was quick.



● Overview of experiments in the QICS project.

A boreholes was drilled to release CO_2 at a horizontal distance ofapproximately 350 m offshore from the coast and at a water depth of 10～ 12 m (depending on the tide level), 12 m below the seabed.

Source: prepared with reference to images, etc. from https://www.rite.or.jp/news/press_releases/pdf/press20140929.pdf

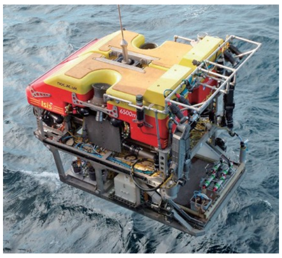
.(2) Scotland case study (STEMM-CCS).

Monitoring was conducted using AUVs and ROVs to experimentally release CO_2 from beneath the seafloor and investigate whether the release point could be detected and whether there were any effects.

Equipment was transported by ROV and installed on the seafloor.
Data was collected using an AUV equipped with various instruments, and images of the seafloor were captured.

● AUV used in STEMM-CCS

Aerial weight:70-88 kg, length 2.7 m, diameter 20 cm. Can dive 500～ 1000 m, can last 4～ 5 hours at 3 kts.
Source: Anita Flohr et.al (2021) Towards improved monitoring of offshore carbon storage: a real- world field experiment detecting a controlled sub- seafloor CO_2: release", International Journal of Greenhouse Gas Control.106

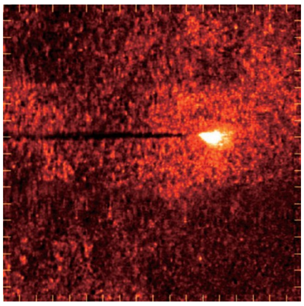


● ROVs used in STEMM-CCS

Monitoring surveys were carried out in STEMM-CCS using AUVs for seepage detection and impact assessment. The AUVs were equipped with sub-bottom profilers to image the seabed in and around the release point, side-scan sonar to survey the surface profile of the seabed and observe the water column and pH sensor to collect spatial pH distribution data in the experimental area. The ROV in the photo has an airborne weight of 4000 kg, a size of 2 m x 2m x 2.5m, equipped with cameras, lights, thrusters, manipulators and numerous scientific sensors, capable of descending to a depth of 6500m.

(3) UK case study (ETI-MMV).

CO_2 was released from the seabed and monitored it using an AUV equipped with a side-scan sonar and chemical sensors. The side-scan sonar automatically detected the CO_2 released at the release point and captured high-resolution images. The release location was successfully identified.



● Images of CO_2 release
Image taken by the onboard side-scan sonar, showing the acoustic shadow of CO_2 plume.
(shadows caused by obstructed sound = black line).
Source: Marcella Dean et al. (2020) "Insights and guidance for offshore CO_2: storage monitoring based on the QICS, ETI MMV, and STEMM-CCS. projects".

● AUVs used in the ETI-MMV (ALR)
Airborne weight 600～ 1200 kg, length 3.7 m, range 1000km, depending on the type of sensors used and operations, can be deployed for 3 months. Source: National Ocean Center HP.

point

Advantage 1: Mechanization is expected to reduce the monitoring cost burden
Advantage 2: Data can be obtained even in difficult-to-survey areas, such as the seabed.
Advantage 3: Although it is not efficient for detecting seepages in unspecified locations, it is highly effective for determining whether a seapage is coming from a known location or whether it is a stored substance, or for identifying the seapage location.
Issues: Research is being conducted in collaboration with JAMSTEC and others under the Cabinet Office's Strategic Innovation Promotion Program (SIP), but still in its early stages. The specific outcomes and domestic application of this research remain to be determined.

Reasonable monitoring approach.

So far, we have introduced monitoring technologies and mentioned the importance of gaining stakeholder understanding, but another important aspect of monitoring is to consider business viability (managerial aspects). The monitoring required depends on the geological characteristics of the CCS site, the social environment and other factors, so a monitoring plan must be drawn up for each site.

The first step is then to monitor the operating conditions and carbon dioxide movements to ensure that the various data are within the expected limits (primary monitoring.) When data deviating from the assumptions are identified, the risks are assessed and, if necessary, additional monitoring is carried out (secondary monitoring.) On the other hand, if it can be determined that there is no risk during the course of operation, the degree of monitoring may be reduced. In this way, setting monitoring items and monitoring content appropriately and flexibly based on risk assessment over the operation period will contribute to improving business viability.

In addition, as projects regarding CCS are new and unfamiliar to the general public, it may be necessary to consider adding items based on social concerns (e.g. monitoring of corals) as monitoring items, apart from the monitoring regulated by the law, in relation to stakeholder understanding.

In this way, monitoring items that are judged to be comprehensively necessary should be planned in a way that suits the site, and their content is reviewed and implemented as appropriate. This is the ideal form of monitoring.

Expert member of the Advisory Committee on issues related to the Tomakomai CCS demonstration project

((○: Member of subcommittee on monitoring for future implementation of CCS, concurrently serving as member of other subcommittees)

31/03/2024 Current

○ Dr. Kozo Sato (Chairperson)	Graduate School of Engineering, The University of Tokyo Professor, Department of Systems Creation Studies
○ Dr. Hideshi Kaieda	Honorary Research Advisor, Central Research Institute of Electric Power Industry
○ Dr.Toru Sato	Graduate School of Frontier Sciences, The University of Tokyo Professor, Department of Ocean Technology, Policy and Environment
○ Dr.Jiyu Xue	Chief Researcher, Research Institute of Innovative Technology for the Earth
○ Dr.Masao Sorai	National Institute of Advanced Industrial Science and Technology (AIST) Principal Rerscher & Group leader, CO_2 Geological Storage Research Group
○ Dr.Tomoyoshi Tokunaga	Graduate School of Frontier Sciences, The University of Tokyo Professor, Department of Environmental Systems
○ Dr.Toshifumi Matsuoka	Special researcher, Fukada Geological Research Institute Professor Emeritus, Kyoto University
Mr.Yukio Kishimoto	Senior Advisor, NUS Co.
Dr.Takao Nakagaki	School of Science and Engineering, Waseda University Professor, Department of Integrated Mechanical Engineering, Faculty of Creative Science and Engineering
Dr.Tetsuro Fuchino	School of Materials Science and Engineering, Tokyo Institute of Technology Associate Professor, Department of Applied Chemistry

[Ref.

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CLIP1 'Where does CO_2 get trapped?' CLIP2
'Explanation of reservoirs and shielding layers'
CLIP3 'Investigation of storage sites'
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This booklet was prepared by Japan CCS Research Ltd. as part of a commission by the New Energy and Industrial Technology Development Organisation (NEDO).

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