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Ministry of Economy,
Trade and Industry
METI

IEA GREENHOUSE GAS R&D PROGRAMME

Building Confidence in
Geological Storage of Carbon Dioxide

Date: June 2007

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National institute of Advanced Industrial Science and Technology of Japan
Quintessa Japan
Quintessa
JGC Corporation
Mitsubishi Research Institute, inc.
Mizuho Information and Research Institute

Further information or copies of the report can be obtained by contacting the IEA GHG R&D Programme at:

IEA GHG Greenhouse R&D Programme, Orchard Business Centre,
Stoke Orchard, Cheltenham Glos. GL52 7RZ. UK
Tel:+44 1242 680753 Fax:+44 1242 680758
E-mail:mail@ieaghg.org
www.ieaghg.org.uk

Foreword

Background and Objectives of Building Confidence in Geological Storage of Carbon Dioxide

In recent years, carbon dioxide capture and its geological storage (CCS) has been recognized as one of the most effective tools to mitigate climate change with its vast potential and cost effectiveness. With this background, many countries around the world have started to study on its technical aspects as well as economic aspects. In some countries, several commercial or experimental plants are already implemented and operated. In addition, many international cooperation activities on CCS are being undertaken or planned. Like EU's new energy policy, governmental policies now also accelerate the introduction of CCS. In the meantime, many people still do not fully understand technical details of the CCS and may feel worry about its possible seepage of stored CO2 in the long-term future.

Indeed, *Decision 1/CMP.2 Further guidance relating to the clean development mechanism* invite intergovernmental organizations and non-governmental organizations to provide to the secretariat, by 31 May 2007, information addressing the following issues:

(a) Long-term physical leakage (seepage) levels of risks and uncertainty;
(b) Project boundary issues (such as reservoirs in international waters, several projects using one reservoir) and projects involving more than one country (projects that cross national boundaries);
(c) Long-term responsibility for monitoring the reservoir and any remediation measures that may be necessary after the end of the crediting period;
(d) Long-term liability for storage sites;
(e) Accounting options for any long-term seepage from reservoirs;
(f) Criteria and steps for the selection of suitable storage sites with respect to the potential for release of greenhouse gases;
(g) Potential leakage paths and site characteristics and monitoring methodologies for physical leakage (seepage) from the storage site and related infrastructure for example, transportation;
(h) Operation of reservoirs (for example, well-sealing and abandonment procedures), dynamics of carbon dioxide distribution within the reservoir and remediation issues;
(i) Any other relevant matters, including environmental impacts;

With this background, METI (Ministry of Economy, Technology and Industry) made significant efforts for confidence building in the past years. Firstly, NEDO (New Energy and Industrial Technology Development Organization) on behalf of METI presented a proposal on confidence building on CCS initiative at the 30th Executive Committee Meeting of IEA GHG R&D Programme. Based on this proposal, a special session was prepared at the IEA GHG 2nd Risk Assessment Network Meeting, Oct 5th-6th 2006 at Lawrence Berkeley National Laboratory in San Francisco U.S. and active discussion was made on methodologies, international cooperation and its implementation on CCS confidence building. Then, in Oct 24th in Tokyo, a workshop on CCS Confidence Building was organized by METI with participation from both governmental organizations and the private sector. Active discussion was made on safety assessment, natural analogue, risk communication and confidence building. Based on this achievement, an international workshop on confidence building in the long-term effectiveness of Carbon Dioxide Capture and Geological Storage was held in January 24-25th in Tokyo. This workshop invited not only Japanese experts but also experts in the world, such as IEA GHG, Lawrence Berkeley National Laboratory and CO2GeoNet_BRGM. This workshop provided unprecedented opportunity to exchange latest information, vies and ideas on confidence building on CCS. This report is written based on the fruits of this workshop.

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1. **Introduction**

The objective of this report is to summarise activities relating to the development of a methodology and framework for confidence building through construction of a robust set of arguments to support the long-term effectiveness of CCS in the presence of uncertainty and to communicate confidence among various types of stakeholders. The content of the report is based, mainly, on presentations and discussions at the Workshop on Confidence Building in the Long-term Effectiveness of Carbon Dioxide Capture and Geological Storage held in Tokyo in January, 2007.

1.1 Decision under uncertainty

It is impossible to describe completely the evolution of an open system, such as a reservoir and its environment that cannot be completely characterised and may be influenced by natural and human-induced factors outside the system boundaries. A complete description is not, however, a requirement of decision making for the development of a reservoir system for carbon capture and storage (CCS). The development of a reservoir system is an iterative process, so that decision making requires only that a number of arguments for the effective confinement of CO_2 within a reservoir gives adequate confidence to support the decision at hand, and that an efficient strategy exists to deal with any uncertainties which have the potential to compromise effectiveness of the confinement.

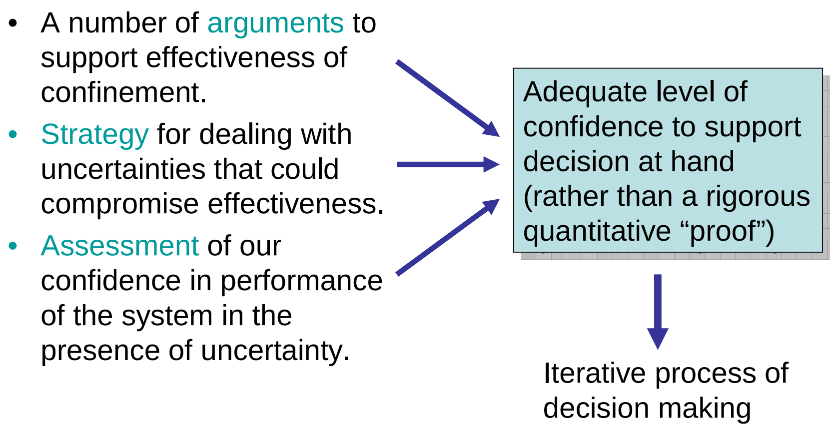


Figure 1-1 Role of confidence building in iterative decision processes. From Takase, 2006.

Our knowledge of the system has been, and will be, evolving in future as more information becomes available. If we assume that the knowledge approaches an asymptotic state after a sufficiently long time, "the ultimate knowledge", then just a part of the current "state of the art" knowledge survives, which is what we understand correctly based on the information available now. The other part is what we misunderstand due to measurement errors, residual errors in approximation, errors in interpretation and so on. On the other hand, due to the complexity of the natural system and the very long timescale of interest, there are things that we do not know. In some cases we can identify possible options of scenarios, models, and parameter values, but we do not have enough information to decide on a specific case. This class of uncertainty is often called *ignorance* or *ambiguity*. In other words, these are what we know we do not know yet. However, sometimes we cannot even specify any options at all. In these situations we do not know what we do not know. This is called *open uncertainty*. Uncertainties also exist with respect to what we understand correctly due to the stochastic nature of the system and its behaviour. This is another important class of uncertainty called *variability* or *randomness*.

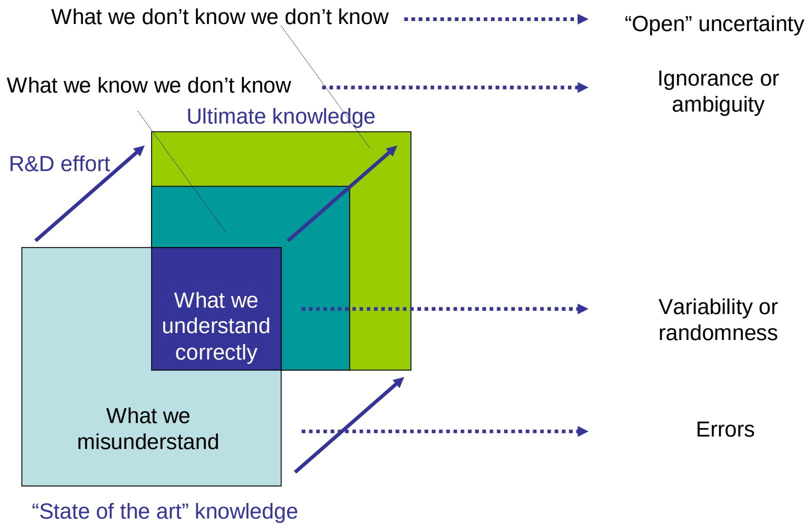


Figure 1-2 Types of uncertainty to be considered. From Takase, 2006.

1.2 Uncertainty management and confidence building

There is a well-known 'duality' between knowledge and uncertainty. So the enhancement of our confidence always requires management of uncertainty. For this purpose, we need to be able to identify all the different types of uncertainties associated with our knowledge, to evaluate their size and their potential impact and also we need to know the way to reduce them if at all possible. A probabilistic framework for quantitative risk assessment is a standard tool to deal with variability or randomness and it can be used for ignorance to some extent. However, we need to be careful for the following two reasons:

- The application of a probabilistic paradigm to events that occur deterministically, but we cannot specify the time of occurrence and their impact due to ignorance could lead to so-called ‘risk dilution’, which is a apparent reduction of risk due to uncertainty;
- Our knowledge has a structure, which is called a ‘knowledge model’, and ignorance is often best represented by the existence of multiple competing knowledge models. The applicability of the stochastic approach to this type of problem has not been proved.

In addition, as for open uncertainty, the way to treat them in a probabilistic framework is not obvious, if not impossible. These observations suggest that an additional methodology would be a useful element of an integrated framework for uncertainty management or confidence building.

Variability	**Ignorance**
• Stochastic nature of the phenomena. • Spatial heterogeneity is an important class of variability. • Probabilistic framework, e.g., geostatistics, is usually used to describe variability. • Variability cannot be reduced by investigation.	• Ambiguity in our knowledge due to imprecise and/or imperfect information. • (Subjective) probabilistic approach or Fuzzy set theory is usually used to describe ignorance. • Ignorance could be reduced by further investigation.

Figure 1-3 Variability and ignorance. From Takase, 2006.

As was mentioned earlier, there is a duality between knowledge (or confidence) and uncertainty. Enhancement of confidence requires our knowledge to be improved by a mutually complementary use of variety of evidence, even though each of which might be imprecise and/or imperfect. At the same time, confidence building requires either reduction of each type of uncertainty or measures to avoid their potential impact to become explicit. For this purpose, we believe that a holistic strategy for various types of uncertainty is necessary. An example of open uncertainty would be unknown discrete features in the cap rock. Then, in this case, 'what if' analyses can be carried out to bound the size of its potential impact. Site investigation, monitoring, natural and industrial analogues, could maximize the chance of realizing those unknown features. On the other hand, if all those independent strands of evidence suggest the non-existence of any detrimental discrete features in the cap rock, then it certainly contributes to the enhancement of confidence. Also a defence in depth concept, for example, the adoption of a reservoir possessing two or more different layers of cap rock, could minimize the impact of this open uncertainty. However, 'ignorance' corresponds to ambiguity in the average properties of a known discrete feature in the cap rock, for example. By definition, the average transmissivity of such a feature should be a deterministic value. But, due to imprecise and/or imperfect knowledge, this cannot be specified. In this case, possibility theory, Fuzzy set theory, or subjective probability, may be used to quantify this uncertainty and its consequence. The acquisition of more data and information would result in reduction of ignorance and, in some cases, change of injection position, for example, could reduce its influence. Errors in measurement, simulation and interpretation may lead to contradictory predictions about the effectiveness of confinement. In this case, verification and validation would provide an opportunity to correct them.

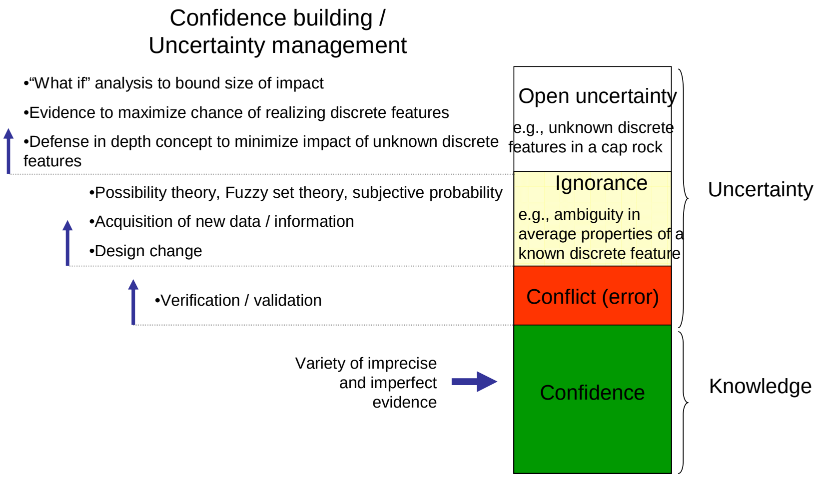


Figure 1-4 'Duality' between confidence building and uncertainty management. From Takase, 2006.

We need a holistic approach to make maximal use of a variety of evidence to support long-term effectiveness of confinement. This requires a comprehensive framework that is much broader than a quantitative risk assessment, where quantitative inputs from various sources such as natural and industrial analogues, monitoring and geological surveys etc, are used directly. What we need is a broader and flexible framework where results of quantitative assessment are referred to as a part of the reasoning to support effective confinement, as well as other evidence, in a mutually complementary manner. Multiple lines of reasoning based on a variety of evidence are necessary in order to develop a robust set of arguments to support the long-term effectiveness in the presence of uncertainty, and to communicate confidence among various types of stakeholders with different value systems.

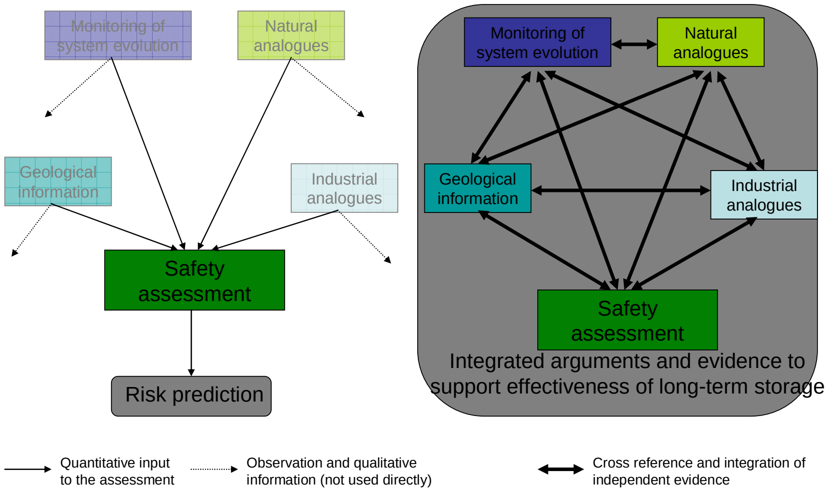


Figure 1-5 Advantage of using 'multiple lines of reasoning'. From Takase, 2006.

In this report, a general methodology and framework that is potentially applicable to confidence building for CCS is reviewed. In Section 2, information-based arguments and evidence that could be referred to in the various stages of confidence building are reviewed. Procedures and methodologies for confidence building through, mainly, argumentation among a group of experts in the areas relevant to CCS are summarised in Section 3. In section 4, confidence building is conceived as a process of knowledge creation within a multi-disciplinary community, aiming towards development of a consensus among broader spectrum of the stakeholders. A variety of aspects are involved in the process of confide building for CCS and there exist issues ranging from those of a purely scientific nature to those relating to socio-political aspects. Studies that are systematically addressing procedure, methodology, and knowledge-base required for confidence building are still at an early stage of development. In Section 5, issues for further research and development are summarised.

2. **Information-base for confidence building**

2.1 Hierarchy of supporting arguments

In this section, an information-base for arguments and evidence supporting long-term confinement of CO_2 by geological storage is reviewed based around a framework presented by Benson (2007), namely, the notion of a 'safety and security pyramid' (**Figure 2-1**), which engenders confidence in the carbon capture and storage (CCS) concept.

At the base of the pyramid lies the *fundamental scientific knowledge of storage and leakage mechanisms*. As Audus (2007) has pointed out, the scientific and technological understanding of CO_2 capture and storage is well-advanced, so that remaining uncertainties relate to convincing the general public that storage is safe and secure, whilst demonstrating the capacity and effective containment for so-called 'saline aquifers'.

Effective site selection and characterisation methods (**Figure 2-1**) were not a principal focus of the Tokyo Workshop, but Czernichowski-Lauriol (2007) emphasised the value of 'norms' (standards) to guarantee local safety for a particular site and to establish transparency and confidence therein. These standards are useful for both national authorities and regulatory organisations to assess CCS projects and impose safety criteria, as well as for storage implementers in the selection of sites, and safety assessment and design of storage operations. Internationally, progress is underway to set these standards through 'best practice manuals' (e.g. Holloway et al., 2005), via experience from industrial and natural analogues and initial CO_2 storage projects (e.g. Sleipner). However, these generic 'standards' may be difficult to establish due to site-specific geological conditions, the complexity of the processes involved, and in some instances, the availability of only partial geological characterisation details. These standards need to be as simple as possible (to enable quick decisions), generic, with flexibility for adaptation to each site under consideration.

Much information for *storage engineering* and *safe operations* (**Figure 2-1**) can be established from the oil and gas industry (Benson, 2007). As Benson (2007) illustrates, industrial and natural analogues are useful for understanding and quantifying risks. For example, the oil and gas industry has a safety record comparable to many ongoing activities, and incidents such as well blowouts are rare events. The safety and security pyramid (**Figure 2-1**) outlines and explains diligent operations, oversight and financial responsibility. Long-term storage security risks can be informed by operational performance from the oil and gas industry. This experience would suggest that the greatest risks occur during operational phase. However, more commercial-scale CCS projects are needed to build confidence.

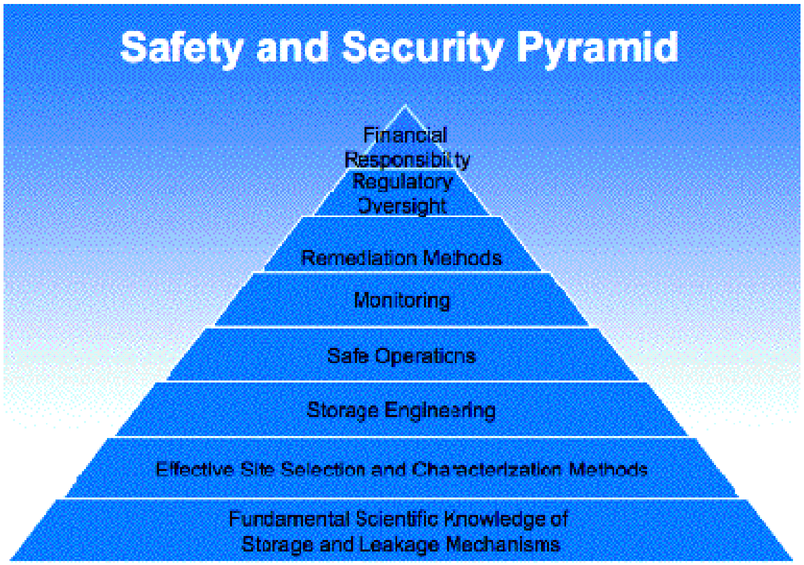


Figure 2-1 The concept of a 'safety and security pyramid'. From Benson, 2007.

Monitoring (**Figure 2-1**) was not a principal focus of the workshop, but recent reviews (e.g. Benson and Myer, 2002; Stenhouse and Savage, 2004; Pearce et al., 2005; Benson, 2006; Pearce et al., in press) have demonstrated that technology is well advanced to monitor the presence of CO_2 underground and to be able to assess leakage with the relevant detection limits. A synthesis of these reviews is presented in Section 2.3.

Remediation methods were not discussed explicitly at the workshop, but recent work in this area is summarised in Section 2.4.

Regulatory oversight (in relation to risk/safety assessment, in particular) was discussed in detail by Stenhouse (2007). Stenhouse (2007) concluded that a phased approach to storage projects is beneficial to stakeholder acceptance, but that safety/risk assessment and its results are not sufficient to install confidence in all stakeholders. To develop technical standards or a flexible protocol-based framework, it is necessary to build on existing documents, such as Best Practice Manuals, and national standards for risk analysis. Stenhouse (2007) considers that monitoring needs to provide quantitative resolution capability to match requirements through confirmation of safety/risk assessment predictions and quantification of migration of CO_2 for GHG inventory purposes.

2.2 Site selection and characterisation

In a review of the status of CCS, Audus (2007) concluded that sufficient geological storage capacity is available, with oil and gas fields providing significant global storage capacity. The potential capacity of reservoirs with saline pore fluids is large, but not well documented. Audus (2007) raised the following issues:

- can the capacity of a store be defined accurately?
- CCS will need to rely heavily on deep saline aquifers, but are these sufficiently, well-characterised? The integrity of short-term injection of CO_2 in saline aquifers at demonstrated at Sleipner and In-Salah has been demonstrated, but additional effort will be needed to quantify both the storage capacity and storage integrity of deep saline aquifers.
- effective containment needs to be demonstrated, with integrity needing to be maintained in future alongside continued oil and gas exploration.

So-called ‘best practice manuals’ being developed for a variety of projects and sites help point the way forward with regard to site selection and characterisation. For example, the SACS Best Practice Manual (Holloway et al. (2005) recommends that it is necessary to characterise the reservoir and caprock on both local and regional scales to elucidate CO_2 migration patterns and overall storage potential. This involves a determination of structure and stratigraphy both within and external to the reservoir, together with the physical properties of both the reservoir and caprock. The SACS Best Practice Manual (Holloway et al., 2005) suggests various recommendations for different aspects of characterisation, based on the experience during the SACS project, where geoscientific appraisal of the reservoir (the Utsira Sand) and its caprock was carried out at a range of scales. The whole reservoir (some 26000 km^2) was mapped and characterised using regional 2-D seismic datasets and well data. More detailed work was carried out around the injection site using a 3-D seismic dataset and more closely spaced well data.

2.3 Monitoring

CO_2 storage sites will need to be monitored to ensure that CO_2 remains safely trapped in the short-term, and to provide confidence in predictions about its future behaviour over the longer term. A geological storage site may need to be monitored for a number of reasons since the rationales for developing monitoring protocols are varied (Stenhouse et al. (2004)). Recent reviews of the rationale and methodologies for monitoring have been provided by Benson and Myer (2002), Stenhouse and Savage (2004), Pearce et al. (2005), Benson (2006), Pearce et al. (in press) *inter alia,* and these studies form the basis of the content presented here.

Pearce et al. (in press) note that monitoring will take place during the pre-injection phase, during the injection stage itself, and during the post-injection phase when injection has stopped, but before it is closed. During the pre-injection stage, when a site is being characterised, monitoring of the reservoir and of surface conditions may take place to establish baseline conditions against which future site performance can be compared. During injection, the main objective of a monitoring programme will be to verify the amounts stored and to ensure that leakage is not occurring. Ideally, the results of this monitoring can then be 'history-matched' against the predicted system behaviour. Monitoring will then continue when injection has been completed to confirm the system is behaving as predicted, through further history-matching, which will lead to greater confidence in predictions of the long-term future behaviour. Potential environmental impacts of the storage site may also need to be monitored and operators will need to provide evidence of a safe working environment.

Benson (2006) has highlighted that the purpose of monitoring will depend upon the nature of interested parties:

- site operators, environmental regulators, and the general public will want to be assured that CO_2 sequestration is safe.
- Mineral rights and surface rights owners want to be assured that CO_2 is not migrating beyond site boundaries.
- Policy makers, carbon credit traders and investors want to be assured that CO_2 is not returning to the atmosphere.

- Reservoir engineers want information to calibrate and validate simulation models of CO_2 plume migration and short-term containment.
- Safety assessors and regulators want information confirming models regarding the long-term fate of CO_2 in the deep sub-surface.

Moreover, Benson (2006) notes that any monitoring programme will have to address the following:

- What information will be needed for the purposes of inventory verification and carbon trading credits?
- What precision and detection limits should be defined?
- What monitoring techniques are available?
- Do available monitoring techniques have sufficient resolution to meet these needs?
- If not, what developments will be necessary?

Monitoring activities are intimately associated with the site operation and via performance assessment studies, and will form the basis for decision-making throughout a project. A monitoring programme will evolve through the project and will support the operational decision-making process, particularly as the project evolves from one stage to the next.

IPCC inventory guidelines conclude that there is not enough information currently available to define default emission factors for geological storage reservoirs and have instead recommended the following guidelines (IPCC, 2006):

- characterise the geological conditions of the storage site and surrounding region in a proper and thorough fashion;
- model the injection of CO_2 into the storage reservoir and its future behaviour;
- monitor the storage system;
- use the results of monitoring to validate or update the models.

2.3.1 Background fluxes and baseline surveys

The distinction of emissions of CO_2 from a geological storage reservoir from those from natural background is a key issue in the definition of any CO_2 monitoring programme. CO_2 is continuously exchanged between the land and ocean surfaces and the atmosphere, such that each year, about 300 billion tones of CO_2 are taken up by photosynthesis, with an equal amount released by respiration and decomposition of organic matter (Benson, 2006). CO_2 fluxes can vary widely, from place to place, day to night, and between seasons. Consequently, any monitoring programme must obtain site-specific baseline data.

Baseline conditions can be defined as the site-specific conditions prior to injection of CO_2 against which future site performance can be compared. The acquisition of baseline datasets will be very closely linked to project design and site characterisation. Near-surface baseline datasets should be conservatively designed to cover all areas of potential future leakage, so that issues not anticipated at the pre-injection stage can still be evaluated in the future (Pearce et al., in press).

2.3.2 CO_2 migration and leakage

Migration and leakage will remain the primary interest of most monitoring regimes during a CCS project. There are two primary pathways for this: abandoned wells; and faults. Leakage from either of these two features is likely to be confined to a small area over the geological storage reservoir. Depending upon the nature of the leak, CO_2 could either migrate laterally beneath shallower, secondary seals, or ascend vertically up higher permeability pathways.

Regarding the temporal variability of leakage, Benson (2006) has shown that computer simulations demonstrate that leakage can be controlled by both self-enhancing and self-limiting processes, but that the rate of leakage would be expected to increase monotonically as brine is displaced by CO_2. Temporal variations will also depend on the nature of the leak, i.e. whether the leak occurs through the inside of the well casing, or through the annulus.

Migration out of the target reservoir or trap, anticipated or otherwise, may necessitate additional monitoring, both to track and refine understanding of the movement of CO_2, and also to help define appropriate remediation plans. Similarly, leakage would also trigger intensification of the monitoring operation.

2.3.3 Detection limits and quantification of emissions

Definition of detection limits and analytical precision is necessary to develop an appropriate monitoring programme. If a detection limit is set too high, it could compromise the effectiveness of CO_2 sequestration and provide uncertainty regarding the applicability of carbon credit trading. On the other hand, if a limit is set too low, then the cost of implementing a monitoring programme may be prohibitive.

As yet, any limits for the monitoring of CO_2 sequestration have not been set. However, Benson (2006) discusses some of the relevant issues. For example, it could be envisaged that a detection limit could be based on some fraction of the background flux of CO_2. However, in areas with high background fluxes, this approach may not provide a stringent level to ensure that carbon sequestration is an effective greenhouse gas mitigation technique. Another scheme could envisage setting a detection limit tied to a leakage rate, but for small storage projects, detecting very small leakages could be too challenging for current technologies. Benson (2006) consider that the following are the most appropriate criteria for setting detection limits:

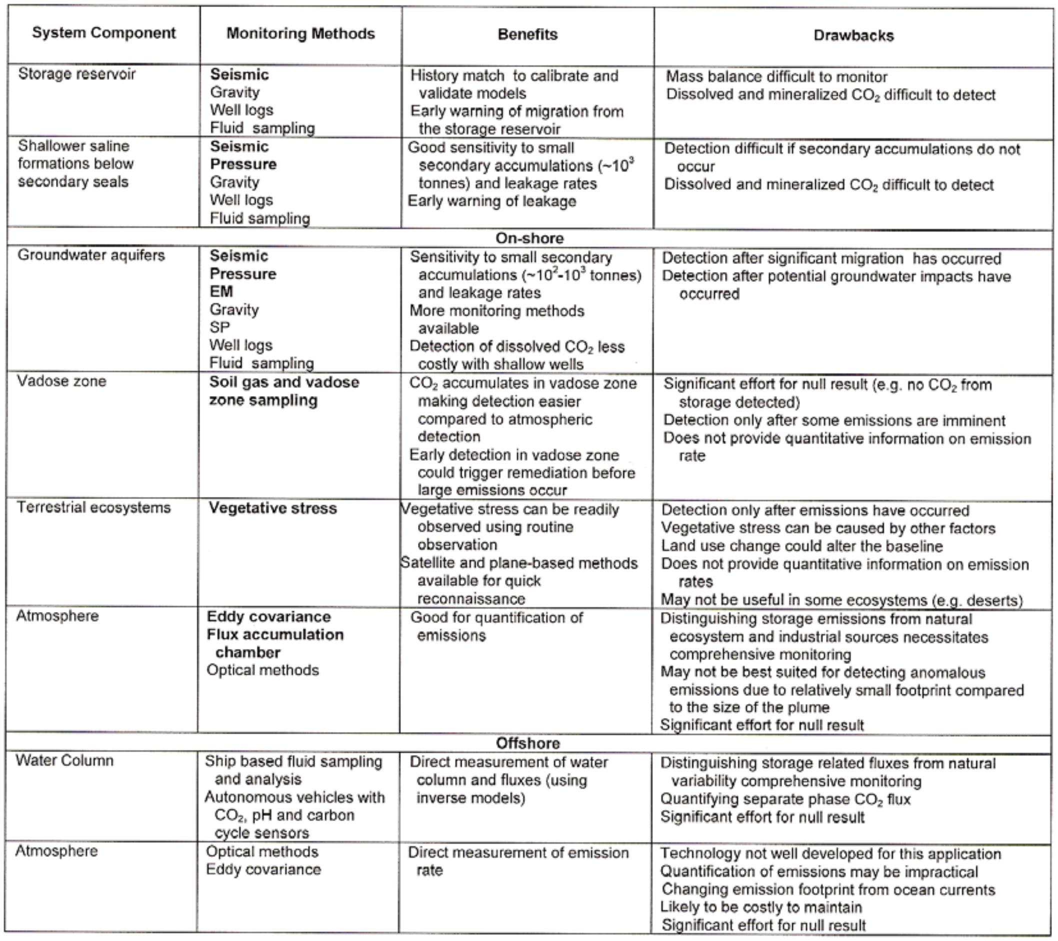
- the approach should be simple with regard to both explanation and implementation.
- It should be defensible, particularly with regard to ensuring the effectiveness of CO_2 sequestration.
- Any approach should be verifiable so that the underlying measurements are reliable and the value of carbon credits can be assigned with confidence and certainty.

Of the various options, Benson (2006) considers that a limit defined as a specified emission for a reservoir per year (e.g. 1000, 5000, 10 000 tonnes per year) is the closest to meeting all of the above criteria.

2.3.4 Monitoring techniques

A number of studies have been carried out to evaluate suitable techniques for CO_2 monitoring which show that a large range of techniques is available at a relatively low cost (US$0.10-0.30 per tonne of CO_2 – Benson (2006). A summary of available techniques is shown in Table 2-1. For example, Benson (2006) has shown that if a storage reservoir is overlain by a saline formation beneath a secondary seal, pressure monitoring and seismic imaging can be extremely effective for detecting migration out of a storage reservoir, particularly near known faults, or abandoned wells. Schematic calculations of pressure increases show that measurable pressure changes (>0.007 bars) would occur within a year for leaking faults located within a kilometre of the injection well for a wide range of permeabilities. Similar calculations show that for leakage around a well casing, there is a high probability of detecting leakage of the order of 5000 tonnes/year at distances of up to 1 km.

Table 2-1 Monitoring approaches and options for measuring emissions from geological storage formations. Methods in bold text are best developed. From Benson (2006).



System Component	Monitoring Methods	Benefits	Drawbacks
Storage reservoir	**Seismic** Gravity Well logs Fluid sampling	History match to calibrate and validate models Early warning of migration from the storage reservoir	Mass balance difficult to monitor Dissolved and mineralized CO_2 difficult to detect
Shallower saline formations below secondary seals	**Seismic** **Pressure** Gravity Well logs Fluid sampling	Good sensitivity to small secondary accumulations (~10^3 tonnes) and leakage rates Early warning of leakage	Detection difficult if secondary accumulations do not occur Dissolved and mineralized CO_2 difficult to detect
On-shore			
Groundwater aquifers	**Seismic** **Pressure** **EM** Gravity SP Well logs Fluid sampling	Sensitivity to small secondary accumulations (~10^2-10^3 tonnes) and leakage rates More monitoring methods available Detection of dissolved CO_2 less costly with shallow wells	Detection after significant migration has occurred Detection after potential groundwater impacts have occurred
Vadose zone	**Soil gas and vadose zone sampling**	CO_2 accumulates in vadose zone making detection easier compared to atmospheric detection Early detection in vadose zone could trigger remediation before large emissions occur	Significant effort for null result (e.g. no CO_2 from storage detected) Detection only after some emissions are imminent Does not provide quantitative information on emission rate
Terrestrial ecosystems	**Vegetative stress**	Vegetative stress can be readily observed using routine observation Satellite and plane-based methods available for quick reconnaissance	Detection only after emissions have occurred Vegetative stress can be caused by other factors Land use change could alter the baseline Does not provide quantitative information on emission rates May not be useful in some ecosystems (e.g. deserts)
Atmosphere	**Eddy covariance** **Flux accumulation chamber** Optical methods	Good for quantification of emissions	Distinguishing storage emissions from natural ecosystem and industrial sources necessitates comprehensive monitoring May not be best suited for detecting anomalous emissions due to relatively small footprint compared to the size of the plume Significant effort for null result
Offshore			
Water Column	Ship based fluid sampling and analysis Autonomous vehicles with CO_2, pH and carbon cycle sensors	Direct measurement of water column and fluxes (using inverse models)	Distinguishing storage related fluxes from natural variability comprehensive monitoring Quantifying separate phase CO_2 flux Significant effort for null result
Atmosphere	Optical methods Eddy covariance	Direct measurement of emission rate	Technology not well developed for this application Quantification of emissions may be impractical Changing emission footprint from ocean currents Likely to be costly to maintain Significant effort for null result

Where secondary seals are unavailable, atmospheric and near-surface monitoring may be a preferred approach, focusing on abandoned wells and surface expression of faults and fractures. Plane-based or satellite-based hyperspectral imaging could be used to locate areas where emissions are likely. If emissions are detected, then the precise location can be determined using flux chambers or soil gas monitoring.

Seismic monitoring can be equally as effective (Benson, 2006). Studies have shown that CO_2 accumulations as small as 100 tonnes could be detected at a depth of about 500 m. Under these conditions, it would be reasonable to conclude that if there were no migration of CO_2 out of the storage reservoir, this should suffice as ‘proof’ that there are no emissions for the reservoir (Benson, 2006).

2.4 Remediation

Any monitoring programme should be intimately linked with remediation plans, since appropriate remediation action cannot be taken without supporting monitoring data. The success of any actions taken must also be measured. As Pearce et al. (in press) have discussed, one important aspect of the remediation plan is the definition of appropriate thresholds, or events, that require some remediation. Accurate, comprehensive baseline monitoring data are crucial in establishing appropriate safety levels or trigger thresholds. Thresholds can be applied to a wide variety of parameters including annular well pressure, microseismicity, soil gas CO_2 concentrations, atmospheric CO_2 concentrations, fluid geochemistry, reservoir pressure or temperature, and tracer concentration. With regard to ecosystems, target indicator organisms could also be selected. Pearce et al. (in press) suggest that activities that could be implemented as a result of reaching a specific threshold or trigger event, could include:

- increasing the frequency of current monitoring,
- implementing additional monitoring techniques,
- revising geological models and storage estimates,
- delay or implementation of the next stage in the project,
- change of operations,
- well work-overs,
- instigating remediation plans and
- informing the regulator(s).

Zhang et al. (2004) have discussed methods for remediation of the vadose zone due to CO_2 leakage. Zhang et al. (2004) liken carbon dioxide leakage plumes to volatile organic compound (VOC) vapour plumes, and suggest that the same remediation approaches are applicable. Leakage will likely lead to secondary trapping in shallower formations, or result in a flow path with a sufficiently long travel time so as to meet the sequestration objective. However, there is a risk that CO_2 leakage will lead to rapid migration upward to the vadose zone. Seepage happens when leaked CO_2 migrates through the vadose zone, reaches the ground surface, and escapes into the ambient air. Seepage of CO_2 can lead to locally high CO_2 concentrations in the near-surface environment, which may cause health and environmental hazards.

Zhang et al. (2004) model results show that, for passive remediation strategies, natural barometric pumping increases the removal rate of CO_2 from the vadose zone. This is because when pressure at the ground surface is lower than the average pressure during barometric pumping, more CO_2 seeps out of the ground surface than the case without barometric pumping. This portion of CO_2 is then diluted immediately by the air in the atmosphere. When the pressure at the ground surface becomes larger than the average atmospheric pressure, pure air (i.e., no CO_2) flows back into the subsurface from the atmosphere. Zhang et al. (2004) showed that pumping from a vertical well increases the CO_2 removal rate slightly. There are two reasons for the limited improvement. First, the gas production from the well (pumping rate) is low and limited by the high aqueous phase saturations around the well, and secondly, the radius of influence of a single well is too small to recover a large gas plume in an efficient manner. When the vadose zone is thicker, it takes longer for the CO_2 to be removed because more of the CO_2 is located farther from the ground surface for thicker vadose zones. When the water table is close to the ground surface (as in this 5 m thick vadose zone case), most of the vadose zone has a very large liquid saturation. This implies a large percentage of the CO_2 plume resides in high liquid saturation regions. Because of the high water saturation, diffusive and advective transport is limited by low gas-phase saturation, and a significant amount of CO_2 is dissolved in the aqueous phase.

The overall conclusion of the modelling studies of Zhang et al. (2004) is that standard passive and active vadose zone remediation strategies will be effective for remediating potential CO_2 leakage plumes in the vadose zone. In detail, the simulation results presented here suggest the following conclusions regarding vadose zone CO_2 leakage plume remediation:

- Barometric pumping enhances the removal rate of CO_2.
- Passive CO_2 removal from high water saturation regions near the water table is limited by low gas saturation and high solubility in groundwater.
- For vapour extraction using a vertical well, the well screen should not be too close to the water table.
- A combination of an impermeable cover and vertical well will improve the removal rate of CO_2 if the well screen is relatively shallow.
- The combination of horizontal and vertical wells is more effective than having either a single horizontal or vertical well.
- Permeability anisotropy ($k_x > k_z$) results in a faster removal rate at an early stage and slower

rate later on.

- The combined vertical and horizontal well configuration would also be effective for VOC contaminants.

2.5 Risk assessment and regulatory oversight

2.5.1 Background

Stenhouse has discussed key issues regarding the role of risk/safety assessment in CCS, from the perspective of key stakeholders (Stenhouse et al., 2004 Stenhouse et al., 2005). Stakeholder acceptance, in particular public acceptance, is considered essential to developing CCS projects in a timely manner. Safety Assessment, as the quantitative method of demonstrating safety, is likely to be a key component of the regulatory approval process and, hence public acceptance. However, safety assessment is unlikely to be the only means of assuring safety and building confidence in CCS projects.

Clearly, there are two key drivers for CCS: greenhouse gas (GHG) mitigation; and consideration of health, safety, and environmental (HSE) impacts. With regard to the former, it is essential that CO_2 remains underground, which requires effective reservoir storage, and moreover, there is a need to be able to account for any CO_2 released back to the atmosphere. With regard to the latter, it is necessary to ensure that CO_2 is not released back to the surface/near-surface environment causing potential harm. This also requires effective reservoir storage. It is noteworthy that the timescales of the two drivers are potentially different. In addition, there may be different stakeholder attitudes to greenhouse gas mitigation on one hand, and local safety impacts on the other.

Regarding timescales, two timeframes are relevant to CCS, depending on the needs of the regulator, whether for GHG reduction inventory control, or for health, safety and environment impacts. That for safety assessment may be in the order of several thousand years, but natural processes exist that can act to reduce the potential hazard over time (**Figure 2-2**).

In essence there are a number of factors/issues that we must consider to develop a meaningful regulatory framework for CCS:

- *carbon dioxide migration* from the reservoir needs to be quantified and it leads to uncertainties perhaps in the level of characterisation away from the storage reservoir.

- *Wellbore integrity* will be a key issue governing successful isolation of CO_2.
- *Monitoring* is an essential component of long-term effectiveness of storage and quantifying leakage and confidence-building.
- *Liabilities* need to be established, both in the short- and long-term.
- CCS needs to be *economically* viable to be successful.
- *Data archiving*, especially for boreholes will also be an essential component of a successful CCS scheme.

So, regarding assurance of safety and confidence, there are essentially no hurdles specific to geological CO_2 storage that have not been addressed in other types of projects, with the exception of CO_2 migration and how this affects GHG mitigation accreditation and accountability. *Only the relevant timeframes are different*. With regard to regulatory oversight, a flexible system is preferable in order to be able to adapt to, and take advantage of, the benefits of increased knowledge from collective understanding and experience of CCS projects.

Risk assessment has a role to play at different stages of any CCS project, starting with preliminary site selection and characterisation, through to detailed characterisation, the licence-permitting phase, through to the post injection phase when the site is closed. Risk assessment has a different role to play in each part, ranging from a simple screening process, and more detailed as a project develops. Safety/risk assessment is important in terms of testing predictions against monitoring experience which is a key aspect of building confidence in a storage project.

It is important to emphasis that risk assessment is an iterative process, so that there are benefits from the information collected at various different stages of the project (**Figure 2-3**). So there are key inputs, ranging from site-specific information, and base line information before CO_2 is injected underground. In the same way, risk assessment can, indeed *should*, direct how a site characterization can be conducted and what type of information can be collected.

2.5.2 Role of risk assessment in the regulatory framework

Stenhouse et al. (2004) has reviewed the existing (regulatory) provisions for authorising CO_2 storage projects, to assess whether these are sufficient and adequate for future implementation of large-scale geologic CO_2 storage projects. In particular, Stenhouse focused on potential lack of communication between regulator and implementer in terms of timeline and also on identification of any gaps associated with safety assessment and its role in regulatory oversight and confidence-building.

In a project feedback questionnaire, regulators from nine countries (Australia, Canada, France, Germany, Japan, The Netherlands, Norway, U.K., U.S.A.) participated in by responding to a variety of topics associated with safety assessment and CCS.

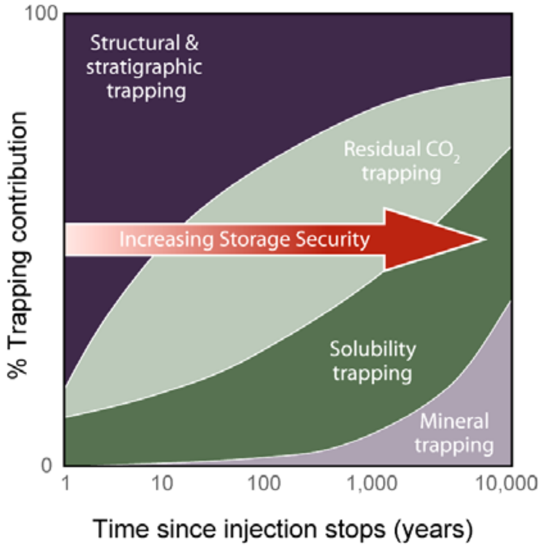


Figure 2-2 Natural trapping mechanisms, including structural trapping, residual CO_2 trapping, solubility trapping, and mineral trapping. From IPCC (2005).

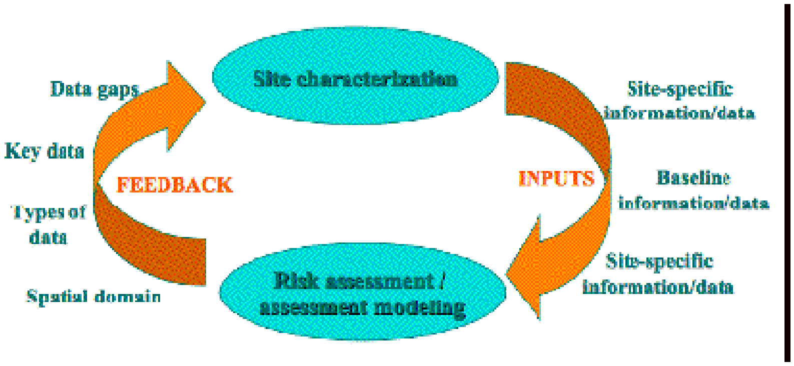


Figure 2-3 The cyclical and iterative nature of safety assessment. From Stenhouse (2007).

The responses of the regulators were supplemented with those of implementers involved in major CO_2 storage projects. Substantive comments were provided in addition to “yes/no” answers.

In general, regulators (and implementers) viewed the assurance of long-term safety to be essential to the successful progress of CCS projects. It was suggested that one way of building confidence was to have a rigorous protocol which should be flexible in its methodology and modelling approach. Also, the link between assessment results and monitoring to confirmation predictions as a means of ensuring safety with regard to potential HSE impacts, was seen as desirable. An integrated ('end-to-end') assessment framework was preferred, where predictions of releases are linked directly to potential HSE impacts.

Specific comments were that the regulator:

- "*should be involved in public communication and safety, by providing as much fact-based information as possible for the public to be aware, and make a determination, of all potential risks*".
- should "*ensure that the project operator......provides adequate information*"
- should "*NOT be a proponent of individual projects*"
- can participate in "*project-specific interaction with the public... …conveying information on a qualitative basis, involving identification of risks and strategies for mitigation*"

Perceived gaps and issues regarding confidence-building amongst regulators were associated with:

- the nature of long-term risks and the associated institutional management.
- Better understanding of timeframes in the context of potential hazards and how these may change with time.
- Well-bore and caprock integrity, especially with regard to long-term storage performance.
- Monitoring, in the context of quantifying CO_2 leakage/migration.
- Improved knowledge of specific environmental impacts, in particular groundwater-specific ecosystems, and offshore environmental impacts.

Many of the above concerns are linked to uncertainties in the long-term predictions and how these uncertainties are communicated to the various stakeholders.

From the perspective of the implementer, the results of the survey suggested that the following may be important gaps in knowledge:

- experience with different types of storage site, particularly deep aquifers.
- Well-bore/seal longevity.

- Quantitative information from natural analogues.
- Fundamental data concerning the thermodynamic behaviour of CO_2, particularly with regard to the effects of impurities, and kinetic data regarding mineral reactions.
- Ensuring that coupling between geochemical and geomechanical processes is included in modelling.
- 'Benchmarking' of safety assessment modelling approaches.

2.5.3 Public awareness

A study carried out in the UK in 2004 found public awareness and understanding to be low; and in the absence of information, people tended not to have an opinion or, if they did, they had a slightly negative view (Shackley et al., 2004).

Provision of some, even limited, information on the topic moves public opinion to a more positive stance, but public support tends to depend on concern over climate change and global warming, with CCS being viewed as one positive strategy. Shackley et al. (2004) further concluded that uncertainties about the potential risks of CCS, in particular the risks of accident and leakage, need to be addressed and reduced.

A study published by Battelle on public attitudes linked to the Mountaineer Project (Ohio, USA) had similar findings (Curry, 2004). Discussion of CCS issues tended to be at national and conceptual level, with little comment at local public level. Local concern was expressed over leakage and the potential for environmental and health effects, such as "*what could be done to minimise their potential /or detect and mitigate their effects if leakage occurs?*".

As part of the IEA Weyburn project, a key activity for Phase 2 (commenced in 2005) is the development and implementation of a public communication strategy (APEC, 2005). At a 2006 Workshop on Public Education and Outreach exercise held by Natural Resources Canada, the key findings were that:

- the framework for public outreach should be broader than just Weyburn to focus on longer term large-scale CCS deployment.
- General education materials on CCS technology should be open, transparent, and unbiased.
- There should be a commitment to an ongoing communication and feedback process for answering questions and addressing concerns.

- Information should be shared with the community before the commencement of a project.

Regarding communication strategies, the Weyburn public outreach programme concluded that a website with opportunities for questions and feedback from ‘experts’ would be useful, with mail-outs to local community and local bulletin boards also being desirable. The survey also indicated that the provision of media articles, preferably using well-known and trusted reporters would be desirable.

For the U.S. Department of Energy ‘Regional Carbon Sequestration Programs’ each partnership has developed a range of public information sources, including fact sheets, interactive websites, video recordings, Town Hall meetings, and focus groups (NETL).

2.5.4 Summary

There are a number of key conclusions:

- A phased approach to storage projects is beneficial to stakeholder acceptance.
- Improved understanding of the processes associated with geological CO_2 storage continues to benefit from the experience gained in pilot-scale and full-scale CCS projects, building on the experience gained from projects such as Sleipner and Weyburn.
- Sharing of project results is extremely useful.
- Safety/risk assessment and its results are not sufficient to install confidence in all stakeholders.
- The inclusion of monitoring and remediation plans in CCS projects is beneficial to overall acceptance.
- To develop technical standards or a flexible protocol -basic framework, it is necessary to build on existing documents, such as Best Practice Manuals, and national standards for risk analysis.
- Benchmarking studies to enhance confidence in different modelling approaches need to be carefully planned.
- Monitoring needs to provide quantitative resolution capability to match requirements through confirmation of safety/risk assessment predictions and quantification of migration of CO_2 for GHG inventory purposes.

2.6 Analogues

Analogues serve a number of purposes linked to safety/risk assessment, with the most quantitative purpose being the validation of predictive modelling results. In the absence of quantitative information, analogues can be used to support risk communication with stakeholders, by identifying geological environments that are suitable for long-term CO_2 storage, and, on the other hand, by explaining why poor sites leak. Moreover, indications are that science-based information is not sufficient to satisfy public concerns, and other avenues of communication, e.g., natural and industrial analogues, are needed to support the science-based approach, particularly when safety assessment techniques are not easy to communicate.

As Czernichowski-Lauriol has pointed out, leakage from geological storage is the main issue of concern with NGOs, the public, government, and regulators (Czernichowski-Lauriol, 2007). Since industrial CCS sites are designed not to leak, there is a need to study natural analogues and conduct deliberate exposure experiments in order to learn what can be measured above baseline conditions.

It is necessary to be able to demonstrate what is, and what is not, measurable and distinguishable from baseline conditions with regard to context, timing, processes, fluxes, impacts, and responses. If it can be claimed that a storage site is secure, it is necessary to be able to demonstrate that this is indeed the case, and beyond reasonable doubt. If it is wrongly claimed or perceived that a storage site is leaking, then it is necessary to be confident that an evidence base can be relied upon to revoke such claims. It is also required to be able to recognise leakage, should such an unlikely event occur, in order to manage safety/risk, address public and stakeholder concerns/interests, and fulfil regulatory obligations.

Within the European ‘CO2GeoNet’ project (http://www.co2geonet.com/), test sites, both natural and experimental, have been identified to tackle leakage and associated Health, Safety, and Environment issues:

- Latera/Ciampino (Italy), the Laacher See (Germany), and Auvergne (France) sites demonstrate leakage from onshore natural gas seeps in various contexts.
- The Gulf of Trieste and Tyrrhenian sea (Italy) sites are submarine natural gas seeps.
- The fjord region off Aalesund (Norway) is the location for marine experiments.
- Montmiral (France) is an onshore natural CO_2 field.

- The ‘Recopol’ site (Germany) is an onshore CO_2-ECBM laboratory.

These sites complement the ‘industrial’ demonstration sites studied in CO2ReMoVe (http://www.co2remove.eu/) and other projects.

For example at Latera, volcanic seepages previously studied in the EU ‘NASCENT’ project (http://www.bgs.ac.uk/nascent/home.html), an integrated cross-disciplinary study is being undertaken, using geochemical, geophysical, remote sensing and ecological studies to characterise migration pathways, leakage rates, and ecological impacts (**Figure 2-4**). An accompanying systems-level model is being developed by to integrate these studies within an overall safety assessment framework.

Yamamoto (2007) has also investigated the rationale for carrying out studies of natural examples of CO_2 leakage and has highlighted the necessity to:

- define what is needed to be known from natural analogues.
- Understand the difference between storage integrity and leakage.
- Understand the dominant leakage pathways.
- Define the typical leakage pattern, both spatially and temporally.
- Define the width of the leakage zone.
- Define the periodicity, duration, and flux of any leakage event.
- Understand how CO_2 affects fluid flow.
- Understand how a trapping mechanism (e.g. solubility, mineralisation etc) works.
- Understand how geological, geochemical, and geomechanical conditions influence the integrity of a storage site.
- Quantify the impacts of any released CO_2.

As an example, Yamamoto (2007) has studied the effects of the 1965-67 earthquake swarm at Matsushiro Japan. Here, 60 000 felt, and additional 600 000 unfelt, tremors were recorded during a five-year period. During the swarm, ten million tons of CO_2-bearing water were discharged at the surface through newly-created surface ruptures over a short period (several months). However, there were no reported impacts on human health or ecosystems. Leakage appears to have occurred through reactivation of a fault, with a relatively rapid cessation of the fluid pulse. Studies conducted by Yamamoto (2007) suggest that groundwater intrusion into the fault may have cause the earthquake. The geological and hydrological conditions of the shallow subsurface appear to have had a significant effect.

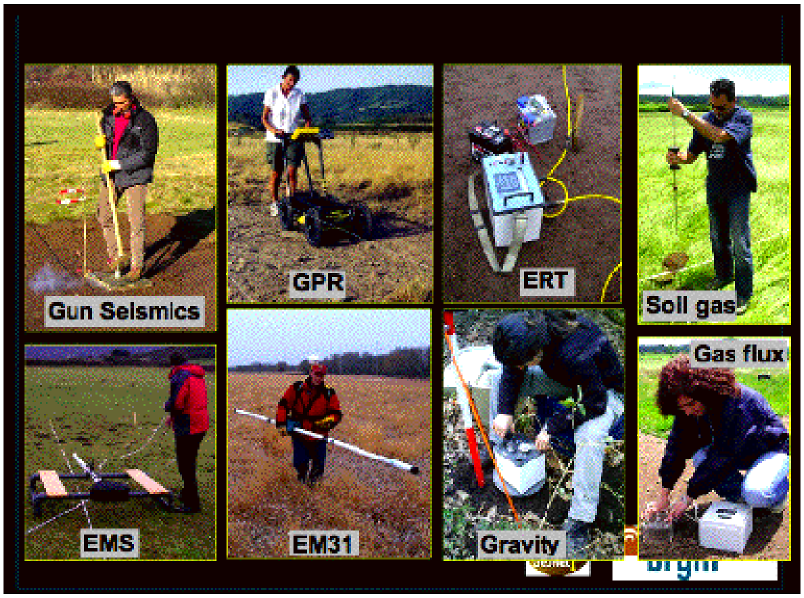


Figure 2-4 Geophysical and geochemical CO_2 monitoring methods being used at Latera through the CO2GeoNet project. Courtesy of CO2GeoNet.

Currently, a very low flux of CO_2 occurs at the surface, but deeper-sourced CO_2 still exists at depth. It seems that dilution and flushing reduced the leakage of CO_2 at the time of the release. Shallow water affected the precipitation and dissolution of carbonates in pore space which enabled sealing of the leakage pathways.

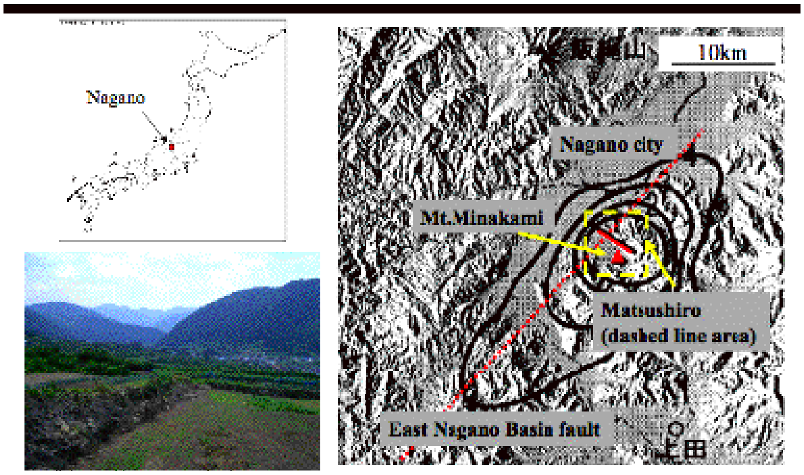


Figure 2-5 Location and environment of Matsushiro 1965-67 earthquake swarm. From Yamamoto (2007).

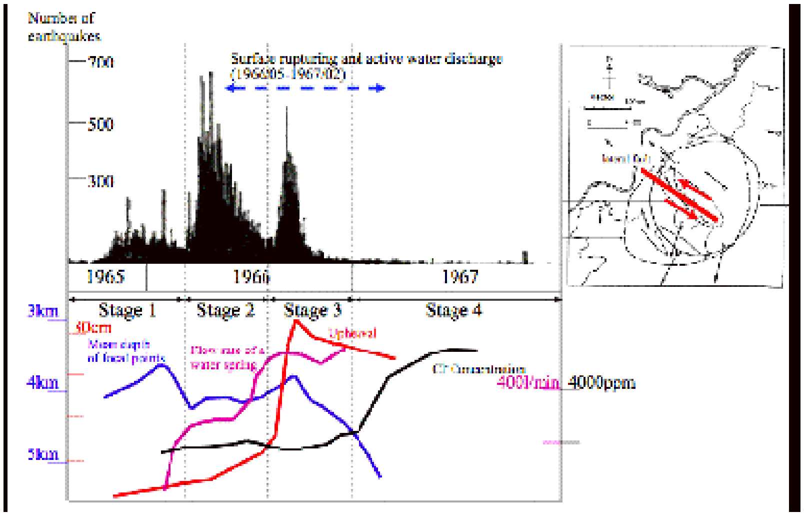


Figure 2-6 Time series change of seismicity, uplift, spring discharge, and salinity (1965-1967). From Yamamoto (2007).

2.7 Industrial analogues

Benson (2007) considers that industrial and natural analogues are useful for understanding and quantifying risks in that the oil and gas industry has safety record comparable to many ongoing activities:

- ▲ well blow-outs are rare events.
- ▲ Long-term storage security risks can be informed by operational performance (greatest risks potentially occur during the operational phase.

More commercial-scale projects are needed to build confidence, with effective two-way communication a strong priority. In this regard, it is necessary to recognize the different concerns of stakeholders.

In conclusion, industrial analogues suggest that CCS activities will have accident rates less than the industry average (Benson, 2007). However, when accidents occur, they are more likely to result in days away from work than the industry average. Fatality rates are typical of heavy industry. Therefore, it is likely that risks of CCS will be comparable to many workplace activities taking place today.

3. **Confidence building through argumentation**

The information-based reviewed in the previous section serves as an inventory of arguments and evidence that could be used as building blocks when we construct multiple lines of reasoning to support the long-term effectiveness of CCS. However, the process of confidence building may not be expedited merely by providing these alone.

Information and knowledge are often used in an interchangeable manner, but some important distinctions exist. Information is data endowed with meaning. In other words, information is interpreted data. On the other hand, knowledge, as in ‘know how’, rather than as in ‘know about’, is directly related to ‘action’. Knowledge in this sense is the capability of a person to take an action. As proposed by Liebowitz (2001), knowledge is ‘the capability to act’. As was described in Section 1, ‘confidence’ is directly linked with some action, so that what is required is not just a collection of information concerning the features and behaviour of natural and engineered systems, but knowledge that empowers us to judge whether a CCS should be implemented or not. Knowledge, unlike information that can be taken away from a person who obtained it and transferred to others who need it, is very much tied up with persons who created it, so that it can only be shared among members of a ‘community’ who also share a variety of information, experience and practice through dynamic interactions (Nishida, 2000). A potentially useful class of such interactions is argumentation that appears to be an adequate model in which the relevant arguments and evidence are integrated in an appropriate context so that they jointly contribute to forming knowledge to judge long-term effectiveness of the confinement to be provided by CCS.

3.1 Rhetorical and dialectical approaches to argumentation

Various philosophers of science assume that the process of resolving a scientific problem can be regarded as conducting a scientific discussion. According to Habermas (1971), the purpose of a scientific discussion of this kind is to arrive at intellectual consensus. De Groot (1984) locates the reasonableness of the scientific method in the fact that an attempt is made to arrive at consensus by means of argumentation in a critical discussion.

In principle, argumentation is a verbal activity, which takes place by means of language use, a social activity, which is as a rule directed at other people, and a rational activity, which is generally based on intellectual considerations. Another important characteristics of argumentation is that it always pertains to a specific point of view, or standpoint, with regard to a certain issue, e.g., long-term effectiveness of CCS in the present case. The proponents of CCS defend this standpoint, by means of argumentation, to audience who may doubt its acceptability or have a different standpoint. The argumentation is aimed at convincing the audience of the acceptability of long-term effectiveness of CCS. In the argumentation, the arguments and evidence summarised in Section 2 jointly constitute a complex speech act aimed at convincing a reasonable critic, and several reasons are put forward for long-term effectiveness of CCS. These reasons can be alternative defences of the standpoint that are unrelated as in 'multiple argumentation', but they can also be interdependent, so that there is a 'parallel chain' of mutually reinforcing reasons, as in 'coordinative argumentation', or a 'serial chain' of reasons that support each other, as in 'subordinative argumentation'.

There are two distinctive approaches in argumentation theory, i.e., the rhetorical and the dialectical models. The rhetorical model comes down to a schematic diagram of the procedural form of argumentation (Figure 3-1), which is generally applicable to most areas of argumentation. In the model, several fixed elements play a role. Facts (data) are adduced in support of a standpoint (claim). The data are linked with the claim by means of a (usually implicit) justification (warrant). In principle, the warrant is a general rule that serves to justify the step from the data to the claim. If necessary, the warrant can in turn be backed up by an additional statement (backing).

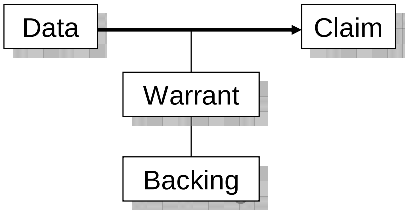


Figure 3-1 Rhetorical model of argumentation. From Toulmin (1958).

The soundness (or validity) of an argumentation is determined, according to Toulmin (1958), by the degree to which the warrant is made acceptable by a backing. The kind of backing that is required depends on the kind of topic that is the subject of the argument. That is why the criteria for evaluating the argumentation are field-dependent. Although the reactions of the others are anticipated, the model is primarily directed at representing the argumentation for the standpoint of the proponent who advances the argumentation. The other party remains passive: The acceptability of the claim is not made dependent on a systematic weighing up of arguments for and against the claim. In the rhetorical model, argumentation is considered sound if it is successful in persuading the audience for which it is intended. Sometimes distinction is made between a ‘specific’ audience whom the proponent addresses in a particular case, and a ‘universal’ audience that is the representation of reasonableness.

On the other hand, the dialectical model describes formal procedures by which it can be dialogically determined whether or not a thesis, e.g., long-term effectiveness of CCS, is logically defensible. In these procedures, the reasoning that takes place is conceived as a dialogue between a proponent and an opponent of a thesis, who join to examine whether the thesis can be successfully defended against critical attack. The proponent has to counter every attack on his own statements by means of a direct attempt of defence or by means of counterattack on one of the opponent’s concessions. The opponent is obliged to defend every concession that the proponent has attacked.

The proponent tries to use the opponent’s concession in such a way that the latter ends up in a position in which the only possibility is to admit to a statement that he had attacked earlier in the discussion. If the proponent succeeds in achieving this, he has won the discussion. In this model, unlike the rhetorical model, the purpose of the argumentation is to examine whether a difference of opinion about the acceptability of a standpoint can be resolved by means of critical discussion, i.e., a regulated exchange of views, in which the parties involved in a difference of opinion systematically try to determine whether the standpoint at issue are defensible in the light of critical doubt or objections.

In what follows, we explain these two models in detail and illustrate their potential use in expediting the process of confidence building referring to a few examples.

3.2 Use of rhetorical model to confidence building for CCS

3.2.1 Hierarchy of arguments and Evidential Support Logic (ESL)

Multiple lines of reasoning based on a variety of sources of evidence are necessary in order to develop a robust argument to support the long-term effectiveness in the presence of uncertainty and to communicate confidence among various types of stakeholders with different value systems. In a recent study, an approach based on ESL (Evidential Support Logic - Hall et al., 1998) was employed to construct and analyse the logical structure of judgments of our confidence and the dependence on various pieces of evidence.

Suppose a proposition is formed supporting long-term confinement of CO_2 by geological storage. The first task of ESL is to unfold this proposition by constructing a process model. The 'top' proposition is subdivided iteratively to form an inverted tree-like structure, with propositions at each lower level corresponding to intermediate interpretations. The subdivision is continued until the proposition becomes sufficiently specific, and evidence to judge its adequacy becomes available.

After constructing the process model, confidence in the top proposition is evaluated. The degree of confidence in the support for each lowest-level proposition is estimated, usually based on expert judgement, from corresponding information (*i.e.* evidence) and propagated through the process model using the simple arithmetic given below. The degree of confidence that some evidence supports a proposition can be expressed as a subjective probability given by experts in the subject area. However, since evidence concerning a complex system is often incomplete and/or imprecise, it may be inappropriate to use the classical (point) probability theory. This theory cannot account for uncertainty in an actual evaluation of support, because if some evidence supports a proposition with probability p, the probability against the proposition is automatically $1-p$. For this reason, ESL uses Interval Probability Theory, which allows one to say "the degree of confidence that evidence supports the proposition lies between p and $p + u$". In this case, the degree of confidence that evidence does not support the proposition is between $1-p-u$ and $1-p$. Hence we have:

- A minimum degree of confidence that some evidence supports the proposition is p;
- A minimum degree of confidence that some evidence does not support the proposition is $1-p-u$;
- The uncertainty is u.

The arithmetic to propagate degrees of confidence upward through the process model is depicted in Figure 3-2, where the 'sufficiency' of an individual piece of evidence or lower level proposition can be regarded as the corresponding conditional probability. That is, 'sufficiency' is the probability of the higher level proposition being true provided each piece of evidence or lower level proposition is true. A parameter called 'dependency' is introduced to avoid double counting of support from any mutually dependent pieces of evidence.

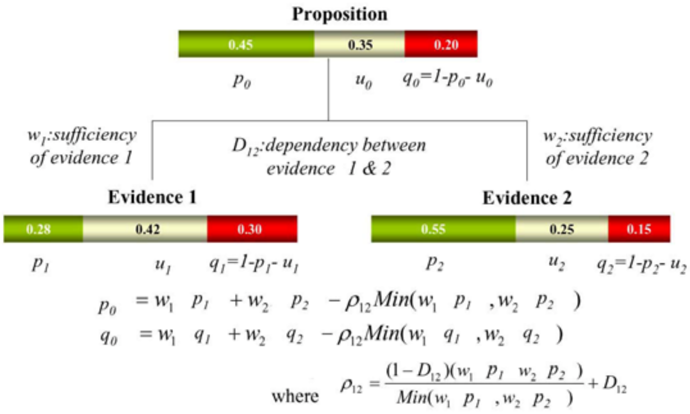


Figure 3-2 Evaluation of confidence using Interval Probability Theory.

The approach based on ESL is applicable to a wide range of technical and non-technical arguments. In a recent study concerning CCS, however, its use is restricted to the former and a group of experts was formed with a variety of expertise ranging from earth science and mathematics to physics. The elicitation process consisted of:

- provision of all the relevant information and related technical articles;
- discussion concerning the structure of the process model for evaluating confidence in each component of the system;
- evaluation of the sufficiency of auxiliary propositions and evidence as well as the subjective probability of each piece of evidence supporting or disqualifying the propositions. The minimum degree of confidence, *p*, is set to be the minimum value of the subjective probability provided by the experts, while the difference between minimum and the maximum value is regarded as *u* whenever the opinions of the experts do not converge.

Figure 3-3 summarises an example of the process model concerning the possibility of a sand layer (‘thief bed’) intersecting a storage reservoir acting as a significant migration path for CO_2 out of the reservoir.

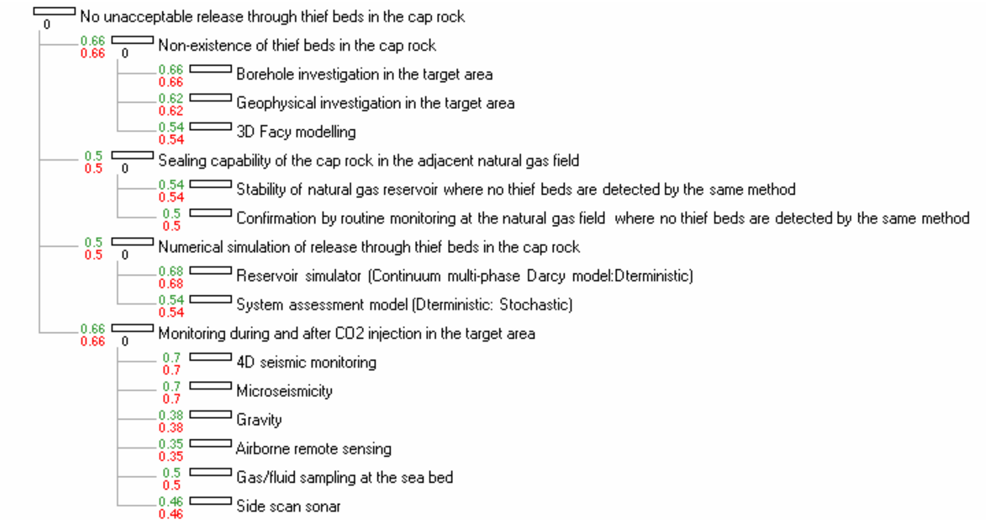


Figure 3-3 Evaluation of confidence based on multiple lines of evidence by ESL. From Takase, et al. (2007).

Numbers associated with each evidence or proposition are ‘sufficiency’, i.e., the probability of the higher level proposition being true (green) or false (red) provided each piece of evidence or lower level proposition is true or false respectively.

It should be noted that results of the ESL evaluation is dependent on the value system associated with members of the expert group and, therefore, can vary. However this is still useful in expediting the communication of confidence among a spectrum of stakeholders in a transparent manner.

3.2.2 Guideline to enhance confidence through uncertainty management

As stated earlier, confidence building is an iterative process where evaluation of confidence based on the evidence available at a stage should be utilised as a useful input to planning of the next stage of the reservoir system development. For this purpose, a sensitivity analysis of ESL can be carried out to evaluate the relative importance of new evidence that could be obtained at subsequent stages. In the case of ESL, by increasing the support from each proposition at the bottom level and calculating how confidence of the top proposition can be improved, the relative contribution of each proposition to confidence enhancement can be evaluated in advance. The sensitivity of each proposition thus obtained reflects efficiency in propagation of the unit increase of confidence affected by sufficiency of all the propositions at the interim levels. Figure 3-4 shows an example of sensitivity analysis using ESL which summarises how confidence in the top proposition can be improved (green) or compromised (red) if a unit increase or decrease respectively in support from each proposition is given. Results of the sensitivity analysis can be used as a basis for prioritising various pieces of evidence that could be obtained at the subsequent stages.

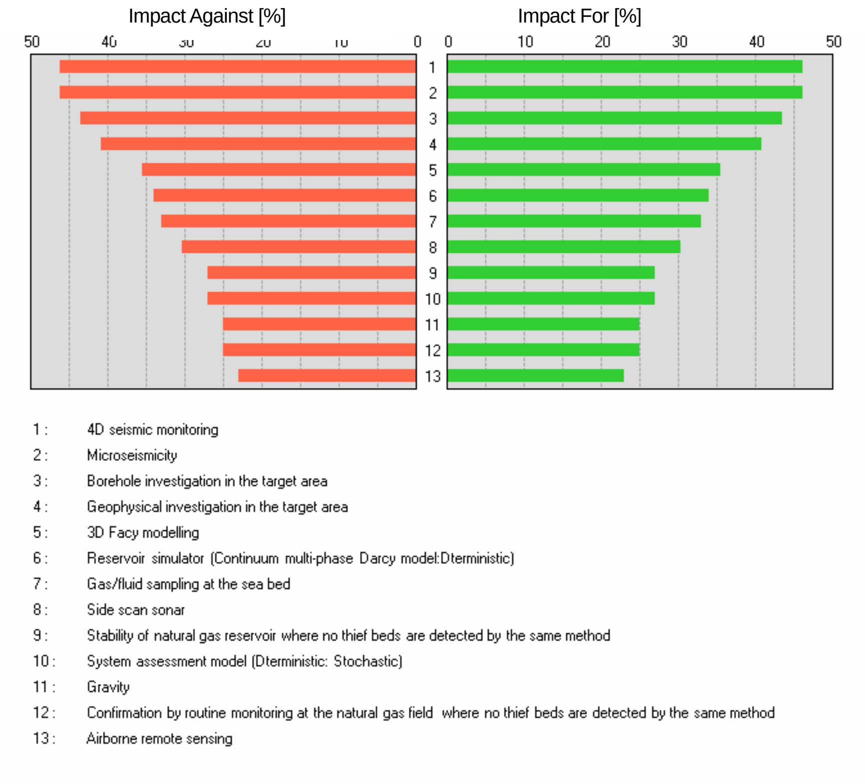


Figure 3-4 Contribution of each piece of evidence to enhancement of confidence. From Takase, et. al. (2007).

3.3 Use of dialectical model to confidence building for CCS

3.3.1 Procedure of dialectical argumentation

According to the dialectical model, the objective of an argumentation is to resolve a difference of opinion. The resolution of a difference of opinion is not the same as the settlement of a dispute. A dispute is settled when, by mutual consent, the difference of opinion has in one way or another been ended – for example, by taking a vote or by the intervention of an outside party who acts as a judge or arbitrator. Whereas a difference of opinion is only resolved if a joint conclusion is reached on the acceptability of the standpoints at issue on the basis of a regulated and unimpaired exchange of arguments and criticism.

The model distinguishes four stages in the process of the resolution of a difference of opinion and the different types of verbal moves that have a constructive function in the different stages of the resolution process (van Eemeren and Grootendorst, 2004):

- In the *confrontation stage* of a critical discussion, it becomes clear that there is a standpoint that is not accepted because it runs up against doubt or contradiction, thereby establishing a difference of opinion. Without such a real or presumed confrontation, there is no need for a critical discussion;
- In the *opening stage*, the parties to the difference of opinion try to find out how much relevant common ground they share (as to the discussion format, background knowledge, values, and so on) in order to be able to determine whether their procedural and substantive ‘zone of agreement’ is sufficiently broad to conduct a fruitful discussion;
- In the *argumentation stage*, proponents advance their argument supporting long-term confinement of CO_2 by geological storage that are intended to systematically overcome the opponents’ doubts or to refute the critical reactions given by the opponents. The opponents investigate whether they consider the argumentation, or parts of it, not completely convincing, they provide further reactions, which are followed by further argumentation by the proponents and so on. In this way, the structure of the argumentation by the proponents put forward can become very complicated. It is critical for the resolution of a difference of opinion that argumentation is not only advanced, but also critically evaluated.
- The *concluding stage* of an argumentative exchange corresponds to the stage of a critical discussion in which the parties establish what the result is of an attempt to resolve a difference of opinion. The difference of opinion can only be considered to be resolved if the parties are, concerning each component of the difference of opinion, in agreement that the proponents’ standpoint is acceptable and the opponent’s doubt must be retracted, or that the standpoint of the proponents must be retracted.

3.3.2 Application to CCS

No attempt has actually been made in applying the dialectical model to argumentation between the proponents and the opponents of CCS in a rigorous manner. Examples so far are limited to the situations in which a subset of the proponents play the role of ‘devil’s advocate’ to raise critical doubts and questions to the arguments that are put forward by the other party. In a sense, the argumentation of this kind is ‘presumed’ rather than real. These, however, still serve as an opportunity to:

- structure arguments in favour of supporting long-term confinement by geological storage;
- test robustness of such arguments and comprehensiveness of the defence against critical doubts and questions;

and, thereby, contribute to enhancing our confidence. In addition, the presumed argumentation identifies open questions, i.e., critical questions that may not be answered based solely on the existing background knowledge (‘threat’), to provide a guideline for further research and development from the perspective of enhancing our confidence further.

In the mode of ‘presumed’ argumentation, emphasis is usually given to the opening stage and the argumentation stage that are explained in detail in the sequel referring to some examples.

(1) Opening stage

As was noted earlier, in the opening stage, the parties to the difference of opinion try to find out how much relevant common ground they share (as to the discussion format, background knowledge, values, and so on) in a ‘real’ argumentation in order to be able to determine whether their procedural and substantive ‘zone of agreement’ is sufficiently broad to conduct a fruitful discussion. In the case of ‘presumed’ argumentation, definition of the common ground that both parties share tends to be implicit since it is assumed that they belong to the same community of practice. However, in order to make the outcome of such presumed argumentation valuable, every effort should be made to define the common ground that they share as explicit as possible. This exercise is useful as well in establishing a common ground among experts from different disciplines in which a key concept could be understood from very much different perspectives and contexts. Such a common ground should include definition of the key concepts such as the reservoir system, the cap rock, structural trapping, and so on. In addition there are other elements that are specifically required for defining the common ground for the dialectical argumentation. One of the most important elements is the ‘argumentation scheme’. Argumentation schemes serve as guidelines of the dialectical chain of argumentation by providing a set of templates for the logical structure of arguments that can be accepted by both parties together with a list of ‘critical questions’ associated with each argumentation scheme. Table 3-1 illustrates an example of argumentation schemes formulated in the area of legal argumentation by Walton (2005). The list developed by Walton (2005) involves argumentation schemes that are generically applicable to other areas. However there is a possibility that some ‘field-dependent’ schemes need to be developed. Table 3-2 is an example that was developed specifically for the purpose of argumentation relating to CCS, although it might be applicable to other issues in which significant uncertainty is associated with the best available knowledge and conservatism need to be introduced into assessment.

Table 3-1 An example of argumentation scheme developed for legal argumentation.

Argument from analogy (Walton,2005）

Argumentation scheme	Major premise: Case C1 is similar to Case C2
	Minor premise: Proposition A is true in Case C1
	Conclusion: Proposition A is true in Case C2
Critical questions	CQ1: Is A true in C1?
	CQ2: Are C1 and C2 similar, in the respects cited?
	CQ3: Are there important differences between C1 and C2?
	CQ4: Is there some other case C3 that is also similar to C1 except that A is false in C3?

Table 3-2 An example of argumentation scheme developed specifically for CCS. From Takase and Savage (2007).

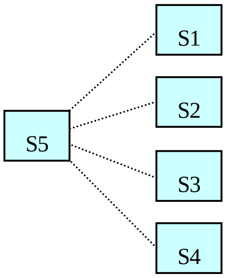
Argument from robustness (Takase, 2007)

Argumentation scheme	Major premise: Proposition A is true if condition X lies between X- and X+.
	Minor premise: Condition X is between X- and X+.
	Conclusion: Proposition A is true.
Critical questions	CQ1: Do we know all the factors that can control X?
	CQ2: Do we know how the factors affect X?
	CQ3: Does X lie between X- and X+ taking into account all the controlling factors and mechanisms?
	CQ4: How strong does the argument need to be with regard to burden of proof?

(2) Argumentation stage

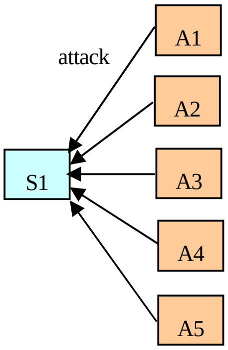
In order to illustrate how the argumentation stage proceeds, an example relating to geological storage of carbon dioxide at a hypothetical depleted natural gas field is described in what follows.

As the first 'move', the proponents of CCS may put forward a confinement strategy based upon the principle that stability of confinement is to be enhanced as time progresses (Figure 3-5. See also Section 2). Then, in turn, the opponents may 'attack' the confinement strategy by initiating critical discussions as in Figure 3-6.



S1	CO_2 is trapped under an impermeable cap rock (Structural and stratigraphical trapping)
S2	CO_2 is trapped within fine pores of the reservoir rock by capillary force (Residual trapping)
S3	Groundwater retains dissolved CO_2 (Solubility trapping)
S4	CO_2 reacts with Ca and/or Mg in the aqueous phase to form carbonate minerals (Mineral trapping)
S5	Enhancement of stability of confinement over time

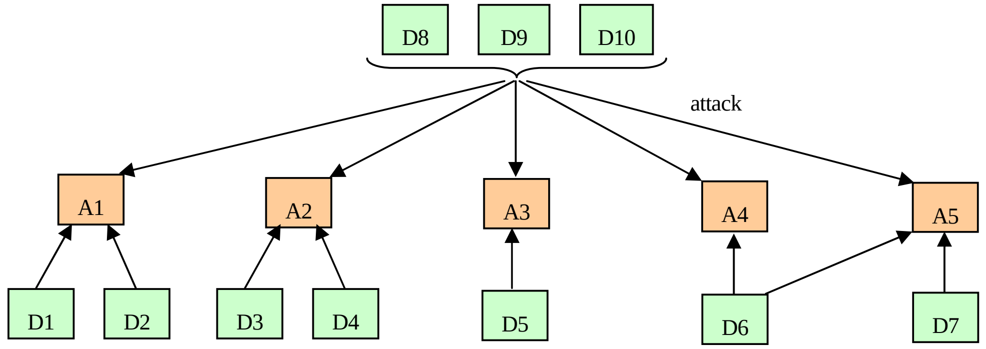
Figure 3-5 The confinement strategy put forward by the proponent. From Takase, et. Al (2007).



A1	Leakage of CO_2 might occur through fractures that are generated by overpressure in the cap rock during injection.
A2	There may be undetected permeable features such as sand and conglomerate layers intersecting the cap rock.
A3	Concrete seal degraded through reaction with dissolved CO_2 may serve as a migration path.
A4	Preferential migration of CO_2 through existing channels in the reservoir may reach the periphery.
A5	Dissolution of minerals in the cap rock may lead to "fingering" that provides preferential paths for CO_2.

Figure 3-6 Possible attacks against the confinement strategy from the opponents. From Takase, et al. (2007).

The argumentation continues further through 'defence' provided by the proponents against the criticism raised by the opponents (Figure 3-7). The defence requires additional arguments and evidence as the backing and, thence, contributes to adding further confidence to the confinement strategy at the top level that was rather abstract at the beginning of the argumentation. This example illustrates 'dialectic' nature of the argumentation process.

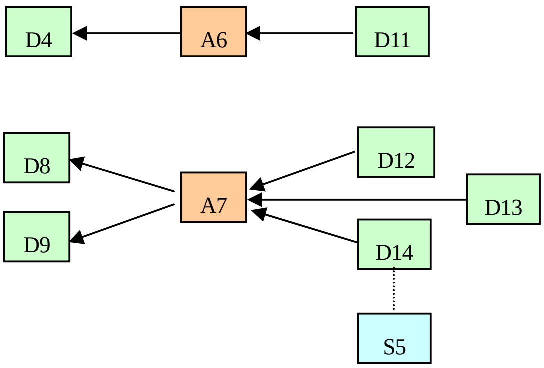


D1	Fracturing of the cap rock can be avoided if injection pressure is controlled adequately.
D2	Injection pressure is to be monitored so that over pressure can be avoided.
D3	No such permeable features have been detected by comprehensive 3D seismic survey in the project area.
D4	The reservoir is a depleted natural gas field and long-term confinement by the cap rock has been validated.
D5	Precipitation of carbonate minerals on the surface of concrete provides dense protective layer and further chemical alteration of the concrete will be suppressed.
D6	Injection pressure of CO_2 is not high enough to migrate beyond the spill point.
D7	Amount of minerals to be dissolved through reaction with CO_2 is not significant.
D8	Unlikely event of CO_2 leakage can be detected by routine monitoring during and after the injection.
D9	Remedial action can be taken for CO_2 leakage in the future.
D10	CO_2 that had leaked from the reservoir dissipates rapidly and its impact on local environment is not significant.

Figure 3-7 Example of defence put forward by the proponents. From Takase, et al. (2007).

The opponents could continue the argumentation by putting forward further 'attack' against the defence provided by the proponents, and the proponents could strike back and so on. Figure 3-8 illustrates examples of further argumentation between the two parties.

In the chain of argumentation, potential threat to long-term confinement by geological storage could be highlighted by stakeholders, so that the technical community has to seek scientific evidence, engineering counter-measures etc. that can provide defence against such threat. In some cases, however, such defence is based only on hypotheses rather than established scientific/technical knowledge. Then what needs to be done is to put a set of possible defences into the dialogue denoting, at the same time, that these are only hypotheses at the moment and to propose a plan for R&D to back them up. This should be regarded as an important knowledge creating mechanism.



A6	CO_2 leakage might occur through abandoned well.
A7	No organization exists that takes legal responsibility of remedial activities against possible CO_2 leakage in the future.
D11	It can be confirmed from the record that all the abandoned wells were properly sealed and it is very unlikely for them to serve as migration paths.
D12	Organizations that can take financial responsibility for future remedial actions continue to exist as long as use of fossil fuels is continued.
D13	After termination of use of fossil fuels, it is unlikely for leakage of CO2 to contribute to global warming significantly.
D14	Since stability of confinement provided by geological storage is to be enhanced over time (S5), it is very unlikely for leakage to occur abruptly in the distant future.

Figure 3-8 Possible further argumentation between both parties. From Takase, et al. (2007).

4. **Concluding remarks ; Confidence building as a knowledge creation process**

A methodology of confidence building with emphasis on knowledge creation through argumentation is proposed in the previous sections, together with an inventory of arguments and evidence supporting long-term confinement by CCS that can be referred to in the argumentation. As was mentioned earlier, knowledge, unlike information that can be taken away from a person who obtained it and transferred to others who need it, is very much tied up with persons who created it and it can only be shared among members of a ‘community’ who also share a variety of information, experience, and practice through dynamic interactions (Nishida, 2000). In order to enhance confidence relating to actions and decisions concerning a multidisciplinary project such as CCS, developing a ‘meta-community’ that integrates existing academic and industrial communities and expedites dynamic knowledge interactions is of crucial importance. Furthermore a variety of non-expert stakeholders also need to be involved in this meta-community. For this very reason, building confidence in CCS requires active participation of stakeholders from different backgrounds and possessing different value systems. As concluding remarks, two directions in confidence building regarded as a process of creating social knowledge that empowers us to judge whether geological storage of carbon dioxide can be counted as an effective measures against global warming, are summarised below.

4.1 Knowledge management in a multi-disciplinary project

The assets of a multidisciplinary community can be classified as either explicit knowledge that can be expressed in terms of language, figures or equations and communicated among members, or tacit knowledge that they acquired through experience and unconsciously have in their brain. Nonaka and Takeuchi argue that active interaction of these two kinds of knowledge is a driving force of creative enterprises (Nonaka and Takeuchi, 1995). They describe a knowledge spiral model consisting of four stages: externalization, combination, internalization, and socialization. At the externalization stage, explicit knowledge is created by representing expertise as explicit concepts. At the combination stage, new explicit knowledge is created by combining existing explicit knowledge. At the internalization stage, tacit knowledge is created by using explicit knowledge to perform tasks in an interpretive fashion. Such tacit knowledge, then, diffuses into a community and new tacit knowledge is created as shared expertise at the socialization stage.

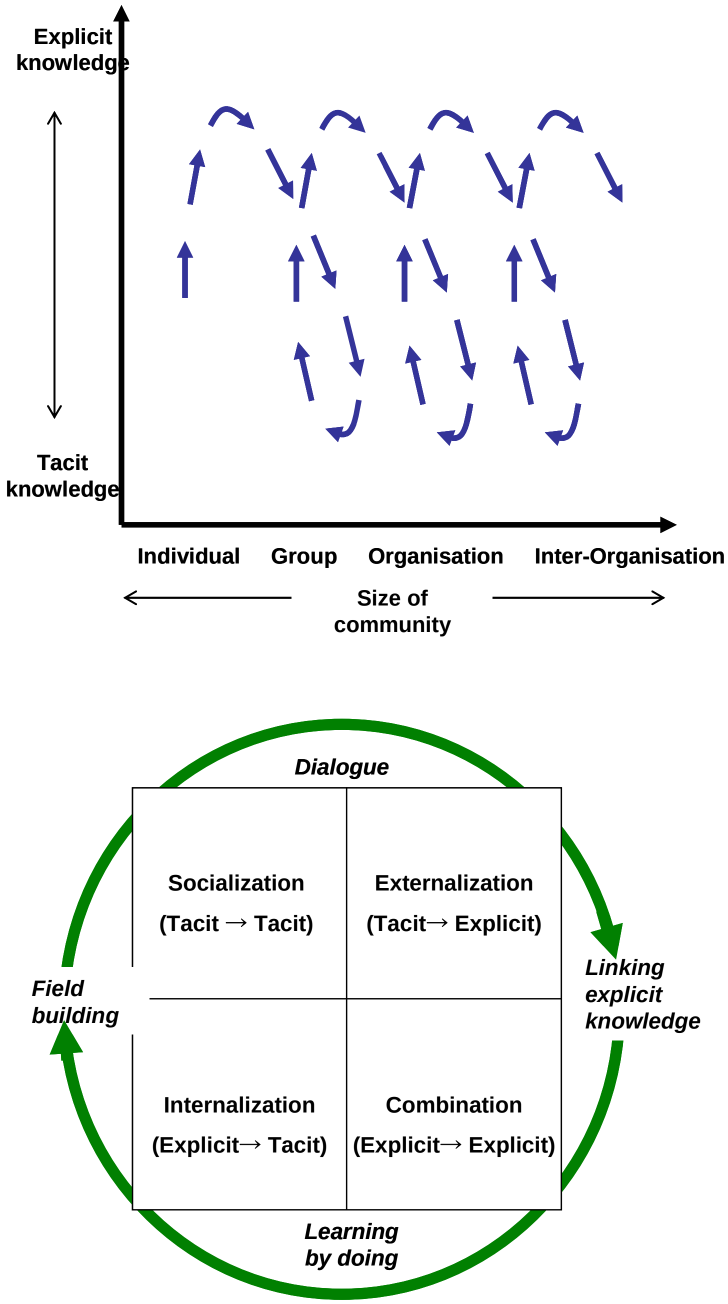


Figure 4-1 Knowledge creating spiral (Nonaka and Takeuchi, 1995).

From the perspective of confidence building, a multidisciplinary research project of a CCS can be regarded as a knowledge-creating community (Nishida, 2000) and networking of various experts relevant to CCS should be encouraged. The essence of knowledge management is how members of the community do the following (da Silva and Cullell, 2003):

- *Generate and acquire knowledge* – this relates to how members measure and foster productivity and creativity, identify weaknesses in their competence and decide how to correct them (e.g., by hiring experts in appropriate fields, training their personnel, incorporating novel technologies, etc.).

- *Store and preserve knowledge* (often quoted as 'organizational learning' – this relates to how knowledge can be preserved within a community once it has been obtained.

- *Access and use knowledge* – this relates to how members identify relevant pieces of knowledge when facing new situations and challenges and what is needed to build a structure such that those pieces of knowledge can be efficiently retrieved when necessary.

- *Distribute and disseminate knowledge* – this is based on the assumption that knowledge is distributed across communities. Hence, different members hold different skills and capabilities. This adds a new dimension to the access and use of knowledge, requiring members to be capable of communicating with each other, expressing capabilities they may need, problems they may be interested in delegating to other members, as well as solutions to delegated problems.

4.2 Chain of trust

There is a hierarchy of issues relating to CCS that are nested in each other. A variety of stakeholders with different interest and value systems have concern in issues at a higher level, e.g., the effectiveness of CCS as a measure to prevent global warming, in which a higher degree of 'publicness' is involved. In order for them to resolve these issues, however, a number of related technical and/or scientific questions concerning, e.g., site characterisation, reservoir engineering and more specific technical/scientific issues, need to be answered. Because of the nature of these questions, most of the stakeholders do not have a direct interest. Through active participation in the knowledge creating process mentioned in Section 4.1, their literacy may be improved to some extent, but it requires significant time and effort for every stakeholder to be capable of dealing with these issues in detail. Therefore it is necessary for them to delegate tasks of answering these questions to those who have relevant expertise. The delegation is possible only when there is 'trust' between experts and non-expert stakeholders based upon fact supporting the arguments, legitimacy and authenticity of their behaviour (Figure 4-2).

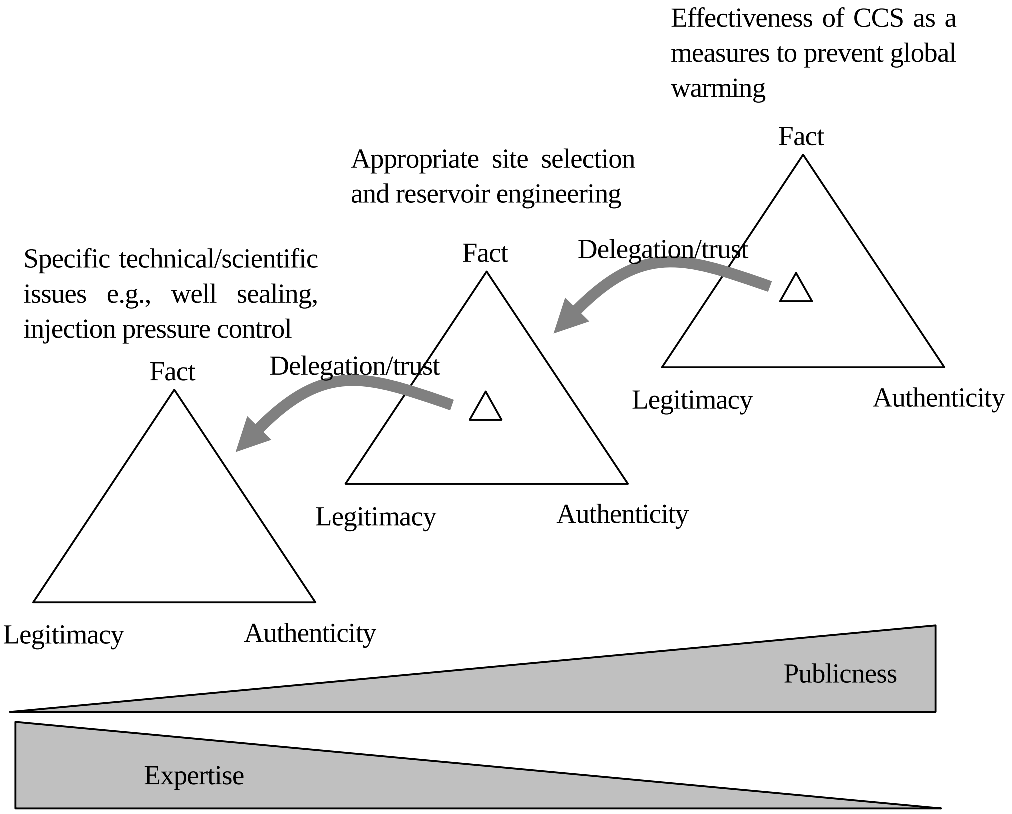


Figure 4-2 Chain of trust through nested arguments.

A variety of questions will be asked by wide range of stakeholders, including those concerning scientific basis for geological storage, monitoring and remediation, legal framework, responsibility to short term socio-economical impacts as well as potential environmental impact in the future, procedure of implementation and decision processes. This is a reflection of the fact that they have a spectrum of concern and opinion depending on their own interest and value systems. Therefore dialogue with them will provide the technical community opportunities to test their arguments from different perspectives, some of which they have never been aware. In most of the cases the questions can be answered and their concern be settled. However, some of them prove to be difficult to answer mainly because the technical community is not aware of the problem. In these cases, it is important to accept perspectives that are totally different from those of the scientific/technical experts and to look for best solution. In order to evaluate their relative weight without biases, perhaps it is important to form a group whose members are from a range of different background (including non-technical ones).

The dialogue with stakeholders should be regarded by the technical community as a mechanism to develop their knowledge through chains of argumentation into common knowledge of a merged 'community' that will be formed in parallel. Since this is a dialectical process of knowledge creation, members of the technical community must not pretend that they knew answers to all the questions asked, or restrict scope of the dialogue to what they think important. On the contrary, they should try to understand value systems that are totally different from theirs and be prepared to accept the existence of open questions.

4.3 International Cooperation

International ccoperation is an important element in the confidence-building cycle. For example, European experts now agree that CCS is a solution to greenhouse gas mitigation (Czernichowski-Lauriol, 2007). This level of confidence has been achieved through large cooperative research programmes including international collaboration as a top priority. Since the initiation of research through the 'Joule II Project' in 1993, a large amount of data and knowledge has been acquired, manifested in nest practice manuals for 'SACS', 'GESTCO', and CO2STORE projects developed through demonstration projects and field laboratories such as Sleipner (Norway), Ketzin (Germany), Esbjerg (Denmark), and Montmiral (France). This research has been extended outside the EU to include research at the Weyburn site in Canada as a priority for the European Community FP 5 research programme in 2001.

Currently, the CO_2GeoNet network of excellence is engaged in a 'knowledge creating cycle' through integration of a multidisciplinary community of researchers across Europe, which share information, experience, and practice through various dynamic interactions (workshops, meetings, etc). Through CO_2GeoNet, a knowledge spiral model has been initiated through externalization, combination, internalisation, and socialization. External collaboration and dialogue with stakeholders is an integral part of this knowledge spiral (Czernichowski-Lauriol, 2007).

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