Carbon Dioxide Capture for Storage in Deep Geologic Formations – Results from the CO_2 Capture Project

Geologic Storage of Carbon Dioxide with Monitoring and Verification

Volume 2

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Geologic Storage of Carbon Dioxide with Monitoring and Verification

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Volume 2

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First edition 2005

Library of Congress Cataloging in Publication Data
A catalog record is available from the Library of Congress.

British Library Cataloguing in Publication Data
A catalogue record is available from the British Library.

ISBN: 0-08-044570-5 (2 volume set)

Volume 1: Chapters 8, 9, 13, 14, 16, 17, 18, 24 and 32 were written with support of the U.S. Department of Energy under Contract No. DE-FC26-01NT41145. The Government reserves for itself and others acting on its behalf a royalty-free, non-exclusive, irrevocable, worldwide license for Governmental purposes to publish, distribute, translate, duplicate, exhibit and perform these copyrighted papers. EU co-funded work appears in chapters 19, 20, 21, 22, 23, 33, 34, 35, 36 and 37. Norwegian Research Council (Klimatek) co-funded work appears in chapters 1, 5, 7, 10, 12, 15 and 32.

Volume 2: The Storage Preface, Storage Integrity Preface, Monitoring and Verification Preface, Risk Assessment Preface and Chapters 1, 4, 6, 8, 13, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33 were written with support of the U.S. Department of Energy under Contract No. DE-FC26-01NT41145. The Government reserves for itself and others acting on its behalf a royalty-free, non-exclusive, irrevocable, worldwide license for Governmental purposes to publish, distribute, translate, duplicate, exhibit and perform these copyrighted papers. Norwegian Research Council (Klimatek) co-funded work appears in chapters 9, 15 and 16.

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Carbon Dioxide Capture for Storage in Deep Geologic Formations, Volume 2
D.C. Thomas and S.M. Benson (Eds.)

Chapter 9

NATURAL GAS STORAGE INDUSTRY EXPERIENCE AND TECHNOLOGY: POTENTIAL APPLICATION TO CO_2 GEOLOGICAL STORAGE

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ABSTRACT

This chapter reviews the portfolio of technologies available within the underground gas storage industries in the United States, Canada, and Europe and evaluates their applicability to geologic CO_2 storage. Gas storage operators have accumulated a significant knowledge base for the safe and effective storage of natural gas. While gas leakage has occurred due to well failures and geologic factors, overall gas storage has been effectively and efficiently performed for over 90 years. There are three types of "gas movement" described in this summary; (1) gas leakage—defined as unwanted gas movement through an intended cap rock (2) gas release—defined as leaking gas having escaped to the atmosphere, and (3) gas migration—unwanted gas movement within a reservoir but contained within the reservoir. Only 10 of the approximately 600 storage reservoirs operated in the United States, Canada, and Europe have been identified to have experienced leakage, subject to the ability to detect such leakage by monitoring, material balance, and other methods. Most gas leakage incidents in underground natural gas storage operations have occurred due to wellbore integrity problems. Poor cement jobs, casing corrosion, and improperly plugged wells in converted oil and gas fields have all contributed to gas leakage. Remedial action procedures and technologies to address these problems are well established in the oil and gas industry and have been proven to be effective. It is of special note that leakage of natural gas has occurred in at least one field despite application of practically all available technology and integrity determination techniques. Accordingly, the caution directed at the gas storage industry by Dr Donald Katz in the 1960s is applicable to the newly developing carbon dioxide (CO_2) storage industry today. Katz essentially warned that zero leakage is difficult to verify and impossible to guarantee. Assuring rapid detection and repair of any potential leaks is more realistic. A number of technologies developed by the underground gas storage industry in the United States and Europe have been identified as having potential application to geologic CO_2 storage. We have identified 24 technologies or technology areas as having application to geological CO_2 storage. Of those, five technologies/techniques were determined to be most relevant. The five most relevant technologies are: "Watching the Barn Doors" (utilization of all techniques on a continuous basis), gas storage observation wells, pump-testing techniques, cap rock sealing (important approaches have been developed in this area but successful sealing has not been achieved), and surface monitoring.

INTRODUCTION

A variety of technologies have been developed over the past 90 years for the underground storage of natural gas (methane) for use during periods of high demand, cold winter days, and peaking needs such as electricity generation. The purposes of this study were to determine what gas storage technologies have been developed and to identify potential applications to geologic storage of CO_2.

Abbreviations: CCP, Carbon Capture Project; DOE, Department of Energy; 4D, four dimensional; 3D, three dimensional; VSP, vertical seismic profiling.

STUDY METHODOLOGY

The methods utilized for this study were as follows: (1) review the relevant literature; (2) survey operators in Europe and Canada; and (3) survey and interview US operators. The surveys and interviews focused on the identification of relevant technologies and the applicability of underground natural gas storage technology to geological CO_2 storage needs. Fifty-five operators in 16 countries were contacted and 42 provided information for the project. A complete list of the literature and results of the surveys are provided in "Final Technical Report: Gas Storage Technology Applicability to CO_2 Storage" [1]. A summary is provided here.

There are three primary types of gas storage fields:

- abandoned oil and gas fields converted to gas storage,
- aquifers (mainly saline aquifers), and
- salt caverns.

Figure 1 shows the types and locations of natural gas storage projects in the United States. Of the 595 underground gas storage facilities in the United States, Canada, and Europe, the majority are converted oil and gas fields, and approximately 40 are aquifer storage projects [2].

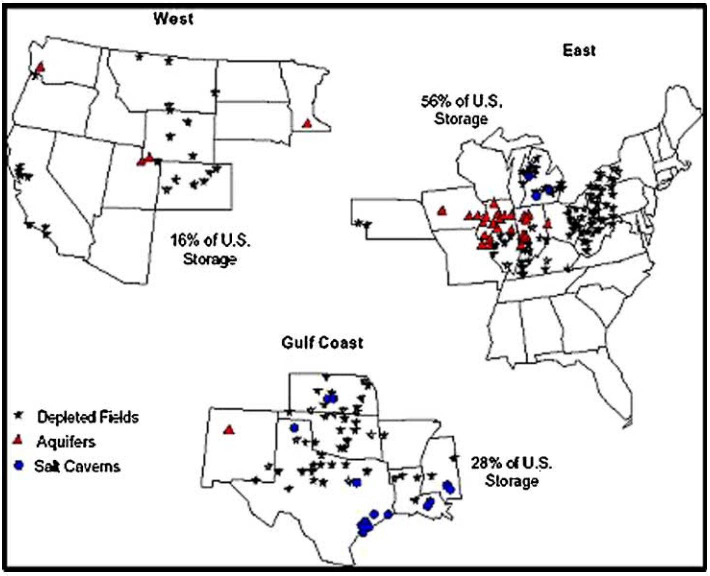

Figure 1: Location, number, and type of underground natural gas storage projects in the United States [2].

Some of the issues operators of geologic CO_2 storage facilities will face are similar to those experienced by gas storage operators. Both are concerned about

- the leakage of injected gas over time,
- monitoring the location of the gas,
- integrity of cap rocks, and
- monitoring of zones above cap rocks for leakage.

Gas storage technologies can therefore make a significant contribution to the technology needs of the geologic CO_2 storage industry. In particular, the significant technology development that occurred during the early stages of development of natural gas aquifer storage projects should be relevant to geologic CO_2 storage. These technologies are unique to the natural gas storage industry and are not generally practiced by the oil and gas exploration and production industry.

RESULTS AND DISCUSSION

The review of gas storage technologies throughout this report focuses on three major areas:

- gas storage field integrity determination,
- gas storage field monitoring and leak detection techniques, and
- gas storage field operator response to leaks and gas leak mitigation.

Discussion of relevance to geologic CO_2 storage has been integrated throughout the report. Particular emphasis has been placed on the technologies developed by the aquifer gas storage industry. Although the hydrocarbons trapped in depleted fields by definition demonstrate the natural storage integrity of these fields, the operators of these projects have developed and utilized monitoring technologies as well that are included in our analysis.

Injection into depleted oil or gas reservoirs is the most widely utilized method of storing natural gas in geologic formations. This is due to the fact that these reservoirs have effective seals that have prevented the escape of hydrocarbons for thousands of years so that the risk of leakage is minimal. However, there are not enough depleted hydrocarbon fields in areas where natural gas storage fields are needed. The same is also true for geologic CO_2 storage for which the sites are needed in the industrial and highly populated areas where depleted oil and gas fields are rare if present at all.

The gas storage industry has overcome this obstacle in part by creating storage fields in aquifers. The same process is an obvious choice for storage of CO_2 in many of the industrial and high-population regions of the United States and around the world. Storage of natural gas in aquifers is the process of injection of gas into an aquifer under structural conditions that mimic natural oil and gas reservoirs, e.g. anticlinal high or up-dip pinch-outs. In addition, the target aquifer must be free of transmissive faults so that stored gas will not leak through faults. Many fault systems are comprised of sealing faults that provide effective containment of fluids as evidenced by the accumulation of oil and gas within these systems. The challenge for aquifer projects is to prove that a fault system has sealing faults.

The keys to the success of storing natural gas and/or CO_2 in geologic formations are proper site selection and accurate delineation of the host formations to ensure that they are continuous and extend over a wide area without encountering faults or other features that could allow escape of the injected gas.

The storage zone must be contained below impermeable beds, preferably structurally undisturbed, and laterally continuous to allow storage of a large quantity of gas injected continuously over months or years. In addition, for any method of gas storage or geologic CO_2 storage to have value, a reliable monitoring procedure must be available to ensure that the process is following the projected path and to implement early remedial action when required.

A number of technologies developed by the gas storage industry in the United States and Europe have been identified as having potential application to geologic CO_2 storage. Table 1 identifies these technologies.

Migration and Leakage of Injected Gas in Underground Natural Gas Projects

An important finding of this study is that only 10 of the approximately 600 storage reservoirs operated in the United States, Canada, and Europe have been identified to have experienced leakage; four due to cap rock issues, five due to wellbore integrity, and one due to reservoir selection (too shallow). All observed leaks through cap rocks have occurred in aquifer storage fields. Table 2 lists the reported incidents of leaks in gas storage fields, the type of leak, and the mechanism or procedure implemented for control of the leak.

TABLE 1
GAS STORAGE TECHNOLOGIES WITH POTENTIAL APPLICATION TO CO_2 STORAGE

- Inventory verification
  - Pressure–volume techniques
  - Reservoir simulation
  - Volumetric gas in place calculations
  - "Watching the barn doors"

- Gas storage monitoring techniques
  - Vegetation monitoring and surface observations
  - Shallow water wells
  - Gas storage observation wells
  - Well logging
  - Seismic monitoring
  - Gas metering
  - Gas sampling and analysis
  - Tracer surveys
  - Production testing
  - Remote sensing

- Leak mitigation techniques
  - Shallow gas recycle
  - Aquifer pressure control
  - Caprock sealing (not proven technique)

- Caprock integrity techniques
  - Geologic assessment
  - Threshold pressure
  - Production/injection tests (pump test)
  - Flow/shut-in pressure tests
  - Air/CO_2 injection

It should be noted that this list might not include all leaks that have occurred, but is as complete as a literature search and interviews of storage operators (as conducted through this study) could provide.

Many of these gas migration incidents have been discovered by state-of-the-art monitoring technologies utilized by the gas storage industry, and in most cases the gas migration has been successfully controlled. Given the number of gas storage reservoirs in the world, the gas storage industry has an excellent record for the safe and effective storage of natural gas.

The gas storage industry has developed a series of actions to be taken when a leak in a storage field occurs. Emphasis is placed on mitigation techniques for cap rock leaks in particular, as the oil and gas industry has a great deal of experience and capability for addressing well workovers and handling of wellbore leaks.

Mitigation of gas leakage from underground natural gas storage projects
In the case of a leak in an aquifer gas storage field, the following mitigation steps are taken. Many of these steps will apply to leaks from any type of storage field.

1. When the gas leakage is first observed and reported, the geographic area of the leak is surveyed for homes, farms, businesses or other entities that may be endangered by the leak. Local and state officials are notified as necessary to protect the public.

TABLE 2
REPORTED INCIDENTS OF LEAKS, TYPE OF LEAK AND REMEDIATION EFFORTS TAKEN IN GAS STORAGE FIELDS

Field type and location	Type of leak	Remedial action taken
Aquifer Storage Field, Galesville Formation, Midwestern US	Caprock leak	Gas recycle from shallow zones followed by water removal from storage zone for pressure control
Aquifer Storage Field, Mt. Simon Formation, Midwestern US	Caprock leak	Gas recycle from shallow zones above aquifer
Aquifer Storage Field, Mt. Simon Formation, Midwestern US	Caprock leak	Field abandoned after small volume of gas stored
Aquifer Storage Field (Leroy), Thaynes Formation, Uinta County, Wyoming, US	Wellbore leak	Wellbore remediation
Salt Cavern Field (Yaggy), Shallow Salt Zone, Kansas, US	Wellbore leak	Wellbore remediation/abandonment
Aquifer Storage Field, St. Peter Sandstone, Midwestern US	Caprock leak	Zone abandoned, deeper formation developed
Depleted Oil and Gas Reservoir Ontario, Canada	Wellbore leak	Wellbore remediation
Depleted Gas Reservoir, Multiple Formations, West Virginia, US	Casing leaks	Rework/recompletion of wells. Casing defect repair
Depleted Oil and Gas Reservoir, West Montebello, California, US	Improperly plugged old well	Proper plugging of old well
Aquifer Storage Field, Shallow Sand, Northern Indiana, US	Reservoir selected too shallow	Abandon field
Russian Fields		No data available

2. If gas is being injected into the gas reservoir, injection may be temporarily halted or injection into wells in the suspected vicinity of the leak discontinued.
3. If gas leakage is observed during the gas withdrawal season, scheduling of gas withdrawal from the storage field may be accelerated. This can be done in the vicinity of the leak and/or can include the entire gas storage field.
4. An investigation into the source of the leak begins immediately. Wellbores in the suspected area are checked for anomalous pressures. Well logs such as temperature and neutron logs may be run in suspect wells. The neutron logs in particular are useful for determining the presence of shallow natural gas accumulations albeit only in the wellbore vicinity. (Note: Neutron logs detect hydrogen densities in the nearby formation, and thus will not be useful for the direct detection of CO_2. Neutron logs may be useful for detecting CO_2 gas through the displacement of water in some cases.)
5. In the case of a cap rock leak, the local geology is reviewed for the most likely area of gas accumulation above the storage zone. Ideally this geologic assessment has been done previously and is available. The shallow zones to be investigated for accumulations of leaking gas are those that are porous and permeable with some type of cap rock just above to slow down or trap a significant accumulation of

gas. Dr Donald Katz in his gas storage research coined the phrase "the cats (Katz) and the doors" to illustrate the most likely location for accumulation of migrating gas [3]. Figure 2 illustrates the concept. In the analogy, the gas storage reservoir is a large room full of cats (the gas) trying to escape. The door leads to a series of rooms connected by doors of various sizes. If the doors leading from rooms 2, 3, 4, are larger than the door from the main storage room, no cats will accumulate in the intermediate rooms since all the cats passing the first door can pass through the larger ones. The cats will accumulate only in room 5, which has a door smaller than the door of the first room. Similarly, the accumulation of gas above a leaky cap rock will occur only when a cap rock is reached which does not leak, or if it leaks more slowly than the primary cap rock. It is believed that gas migrating through the first, second, and third observation zones might well give a significant pressure perturbation at the start of leakage even without significant gas accumulation. This may not always be the case, however, as leakage has occurred to the surface in some storage fields without any observable pressure change in shallow observation zones [3]. In some cases it is possible for gas to leak from the storage reservoir and accumulate in shallow zones without any gas escaping to the atmosphere. (Note: All fields with leakage reviewed within this report experienced gas escaping to the atmosphere.)

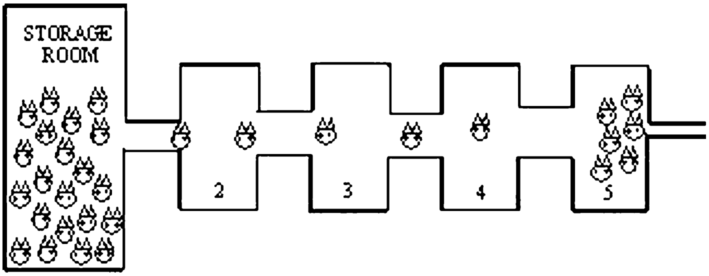

Figure 2: Analogy of "Cats and Doors" to migration and accumulation of gas above a storage reservoir [3].

6. Once the shallow geology is reviewed, a study is conducted integrating all the information on hand. This includes the surface location of the leak in comparison to structural high points in shallow zones and the relative existence and location of permeable zones and cap rocks. Seismic data may be reviewed or new data obtained. From this information, shallow wells are drilled to attempt to locate and produce the gas as it accumulates on its migration path to the surface.
7. Shallow wells that encounter shows of gas after drilling are completed in the gas-bearing zones and production of the shallow gas begins. The process of production lowers the pressure in the zone and helps mitigate further gas movement to the surface. Control of migrating gas has been accomplished at two aquifer fields in the midwestern United States. Locating a shallow zone that is well connected to a significant volume of the leaking gas is an important accomplishment in controlling leakage. This may require the drilling of several wells. Advanced seismic techniques available today may assist with locating shallow gas accumulations.
8. Once shallow wells are drilled and completed, an ongoing gas recycle program is initiated and performed for the remaining life of the storage field or until the leak is located and stopped. In the case of a leak in the cap rock, the recycle goes on for the life of the storage field. Figure 3 illustrates the possible pathway for gas leakage, its accumulation in a shallow zone, and the completion of a shallow well to recover and recycle the leaking gas.
9. Another technique used for control of leaking gas is the continuous withdrawal of water below the gas storage bubble. The removal of a sufficient volume of water lowers the pressure in the gas storage zone to near or below original aquifer pressure. This in turn reduces the volume of gas that leaks through the cap rock, thus controlling the leak. This practice has been put in place at one midwestern gas storage field and continues to be utilized (Midwestern US gas storage operator, personal communication). In this case, the water withdrawn from the zone below the gas bubble in the storage reservoir is injected into shallow zones above the gas storage field.

10. After implementation of a gas recycle program or pressure control procedure via water withdrawal, the injection-withdrawal schedule for the entire storage field may be modified. In particular, the injection season may be delayed as late into the year as possible and withdrawal commenced as early as possible. This has the overall effect of minimizing the time the cap rock experiences high pressure. Another step implemented is to withdraw enough gas every year such that the reservoir pressure is taken below its original pressure each year. This is essential in the case of an aquifer storage project. Yet another step taken to assess the leakage problem is a field-wide shut-in of wells with pressures monitored on each well. The objective is to observe anomalous pressures that may indicate the area of gas leakage.
11. The last mitigation step for leaking storage fields is to identify the location and source of the leak and plug the leak. When the leak occurs due to a mechanical problem in a storage well, repair is accomplished through well workover procedures such as casing patches, squeeze cementing, installation of liners or other accepted practices available from the oil and gas industry. If the leak is through a flaw in the cap rock the problem is much more difficult (see below).

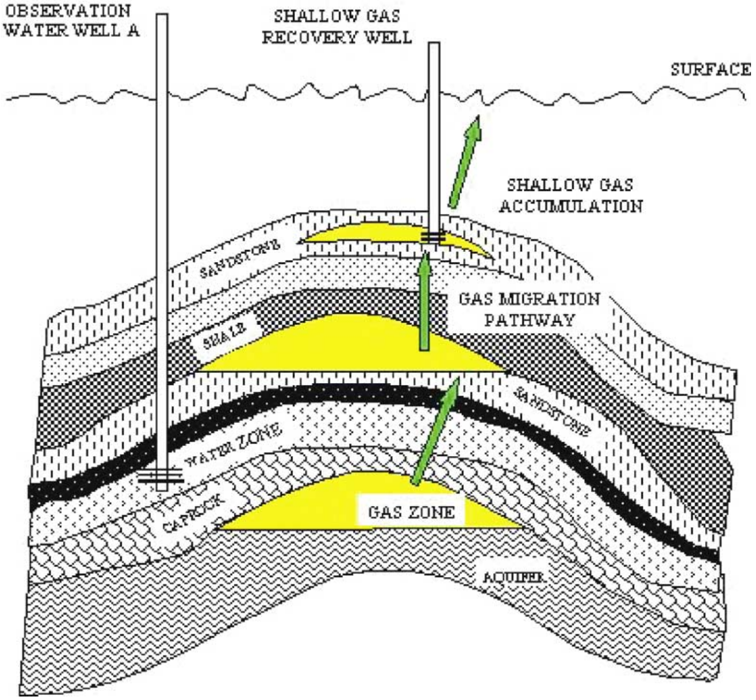

Figure 3: Pathway of migrating gas from storage reservoir, accumulation in shallow zone and recovery and recycle by shallow gas well.

Geologic CO_2 storage needs. Throughout the study, more than 40 participants (which were predominantly gas storage field operators) were asked where they felt the greatest technology needs reside with respect to geologic CO_2 storage. The top 10 needs are listed in Table 3 along with the percentage of respondees selecting each need. The majority of the suggested technological advances involve injection well cementation, completion, inventory verification, and risk analysis operations. Major research efforts are also needed in the development of hardware and software for testing, monitoring, and modeling/simulation.

Important findings for geologic CO_2 storage from gas storage operations. Gas storage operators have accumulated a significant knowledge base for the safe and effective underground storage of natural gas.

TABLE 3
TECHNOLOGY AREAS IN NEED OF IMPROVEMENT FOR CO_2 SEQUESTRATION AS DETERMINED BY SURVEY RESPONSES

Technology	**% of Responses**
Injection well completion	54
Inventory verification	53
Injection well cementation	39
Risk analysis	39
Storage performance	31
Monitoring cap rock leaks	31
Monitoring gas location	31
Simulation	31
Leak response	23
Leak mitigation	23

While unwanted gas migration has occurred both due to mechanical problems with wells and geologic factors, overall gas storage has been effectively and efficiently performed. The following topics are felt to be the most relevant findings from the study regarding gas storage technology application to CO_2 geological storage.

Wellbore gas leakage
Most gas leakage incidents in gas storage operations have occurred due to wellbore integrity problems. Poor cement jobs, casing corrosion, and improperly plugged wells in converted oil and gas fields have all contributed to unwanted gas leakage. Remedial action procedures and technologies are well established in the oil and gas industry to solve these problems, and new technologies continue to be developed to address these issues. Continuous attention will need to be applied to this area by the geologic CO_2 storage industry but practices and technologies exist to remedy gas leakage in wellbores.

Geologically controlled gas leakage
As far as this study could determine, almost all of the geologically controlled gas migration problems have occurred in aquifers being converted to gas storage. In each of these cases the flaws in the cap rock were most likely due to some type of fracturing or faulting associated with the anticlinal structure of the gas storage field. It is important to note that a large anticlinal structure with as many feet of closure as possible is an important criteria for an aquifer gas storage field. It is this feature, however, that introduces the greater possibility of cap rock flaws and potential leakage.

The geologic CO_2 storage industry may find this experience important. Specifically, it may be in the best interest of the geologic CO_2 storage industry to avoid aquifer areas with significant structural features. Gently sloping structure and cap rock formations may be preferable for long-term CO_2 storage.

“Significant structural features” are those with significant structural relief which increases the possibility of faulting or fracturing that may lead to leakage situations through the cap rock.

It is of special note that leakage of gas has occurred (unobserved until significant gas release to the atmosphere was observed) in at least one field despite application of practically all available technology and integrity determination techniques. Accordingly, the caution directed at the gas storage industry by Dr Donald Katz, a pioneer in natural gas engineering and gas storage, in the 1960s is likely to be appropriate for the newly developing CO_2 storage industry today. The caution is quoted below:

> Caution must be exercised in claiming that no gas will ever be found outside the intended well—gathering line—reservoir system. If any gas is found outside the intended system, it is possible that it can

> be handled so as to cause little or no harm, and should be no cause for calling a halt to the operations. Therefore, it is necessary in any full description of a fifty-year life for a storage operation to admit that, on occasions, some gas will enter the waters and even the soil, but that mechanical repairs are available so that the leak can be halted [3]

Testing the integrity of cap rocks above storage zones

The gas storage industry has successfully used several cap rock integrity testing techniques, which are included in Table 1. Each of these techniques can be used individually or combined with other techniques to assure safe storage conditions exist.

The issue of cap rock integrity is where the "rubber meets the road" with regard to storage of gases both for natural gas to be utilized for deliverability needs and for long-term geologic CO_2 storage. The necessity of cap rocks for trapping hydrocarbons is well understood within the oil and gas industry. The gas storage industry has performed research and studied the issue of cap rocks in particular in the area of aquifer gas storage. The interest and need are greatest for aquifer gas storage as there is no natural occurrence of oil or gas to test the integrity or sealing capability of the cap rock.

Potential for assessing field integrity with pilot storage of CO_2 or air

While the natural gas storage industry is required to perform expensive tests to assess field integrity, the geologic CO_2 storage industry is dealing with a noncombustible gas and may not have the need to withdraw gas from storage. This presents the opportunity to test a potential storage site by simply injecting CO_2 and monitoring for pressure disturbances above the zone of interest. If CO_2 is not available at a given site, consideration can be given to injecting air. Air injection is not feasible at a potential natural gas site as the subsequent storage of gas in the presence of air creates the obvious problem of potential unwanted combustion.

A possible procedure is to deploy a portable compressor and one or two wells, one injection well and one observation well, above the storage zone. CO_2 or air could be injected into the potential storage zone creating an over-pressure situation against the potential cap rock. Careful measurements in the observation well above the cap rock can assist with cap rock integrity determination. This type of test could provide significant insight into the integrity and quality of a potential storage site. If air is utilized, it should be kept in mind that CO_2 and air have quite different physical and chemical properties. Air may be very useful for assessing cap rock integrity and basic reservoir properties but would act quite differently than CO_2 in the reservoir, especially deep formations.

Leak mitigation possibilities

The gas storage and oil and gas industries have been successful in repairing wellbore leaks but there is no known case where a geologic leak through a confining layer or cap rock has been sealed. In the case of the oil and gas industry, the need is usually not present, as any cap rock flaw would have precluded the trapping of commercial volumes of hydrocarbons. Without the commercial potential the oil and gas industry has neither interest in these features nor any incentive to investigate cap rock seals. The gas storage industry does have interest in cap rock seals, especially in the aquifer storage area, and has performed limited research.

In the case of aquifers with gas leakage, there have been attempts to determine the location and type of the leak. Tracer surveys, seismic and well tests have been used in this regard. Most of these efforts were undertaken in the 1970s shortly after the development of many of the aquifer storage projects. Little has been done since then due to a lack of new storage development and the application of leak mitigation techniques, primarily gas recapture in shallow horizons or pressure control techniques.

There have been significant advances in recent years in many areas that may allow for the successful sealing of a cap rock leak in the future. Seismic technology has advanced significantly to include 3D and 4D seismic, high-resolution crosswell and vertical seismic profiling (VSP). The technology to carefully drill and steer a wellbore to a given location is available today with a precision unprecedented relative to 1970s technology. Research has been performed on using foams and other materials to control the flow of fluids within reservoirs and wellbores that may eventually lend themselves to the sealing of a geologic fault or fracture. Again, while there is no known successful or attempted geologic fault/cap rock flaw-sealing project, new technologies may open this door in the future where and if it is required. This is an area where the CO_2 storage industry may wish to perform additional research.

Matrix of gas storage technology with applications to geologic CO_2 storage

Table 4 lists the 24 gas storage technologies discussed in the report and notes the application of these technologies for geologic CO_2 storage.

TABLE 4
GAS STORAGE TECHNOLOGIES AND APPLICATION TO GEOLOGIC CO_2 SEQUESTRATION

Gas storage technology area	**Gas in place determination**	**Leak detection**	**Leak control**	**Gas movement monitoring**	**Caprock integrity determination**	**Reservoir suitability for storage**
Pressure–volume techniques	X	X				
Reservoir simulation	X			X		X
Volumetric techniques	X	X				X
"Watching the Barn Doors"	X	X		X	X	
Surface observations		X	X	X		
Change in vegetation		X	X	X		
Shallow water wells		X	X	X		
Gas storage observation wells	X	X	X	X	X	X
Well logging	X	X	X	X		X
Seismic monitoring		X		X		X
Gas metering	X					
Gas sampling and analysis		X		X		
Tracer surveys		X	X	X		
Production testing	X	X			X	
Remote sensing		X	X	X		
Shallow gas recycle			X			
Aquifer pressure control			X			
Caprock sealing techniques		X	X			
Geologic assessment	X	X	X	X	X	X
Threshold pressure					X	X
Pump tests		X			X	X
Flow/shut-in pressure tests		X			X	X
Air/CO_2 injection		X			X	X
Over pressuring					X	X

CONCLUSIONS

Our study resulted in the following conclusions and recommendations:

- The best "early warning signals" for leak detection are observation wells and surface monitoring techniques.
- Control technology for leaking gases from storage operations exists (shallow gas recycle and pressure control). These techniques require continuous, expensive operations and may not be feasible for long-term CO_2 storage.
- All "geologic" cap rock leaks are related to the gas storage need for "steep" structural closure. The geologic CO_2 storage industry (particularly in aquifers) can learn from this experience and significantly mitigate risk.
- Cap rock leak "sealing", while not successful to date, has significant potential through application of newer seismic and well steering for locating and accessing the leak zone. New fluids such as foams and other materials to control fluid flow in the storage zone and the overlying cap rock could then be applied.
- Field-integrity testing should include all available techniques. The design of a pilot test for storage field integrity testing, utilizing the principles of the gas storage industry "pump tests" has potential. Utilization of CO_2 and/or air could provide significant savings.

- Successful monitoring of geologic CO_2 storage projects, as with gas storage, requires a combination of techniques (observation wells, pressure–volume studies, remote sensing). These technologies are available.
- The fact that only 10 gas migration incidents have been reported from operation of approximately 600 storage fields over 90 years of history suggests that natural gas can be safely stored.
- Issues that operators face for geologic CO_2 storage facilities are similar to what natural gas underground storage project operators experience. Both are concerned about:
  - the migration of injected gas over time,
  - technologies for monitoring the location of the injected gas,
  - integrity of cap rocks, and
  - monitoring of zones above cap rocks for leakage.
- Significant technology development has occurred within the natural gas storage industry, especially for aquifer storage, which will have direct applicability to CO_2 storage. The five most relevant technologies/techniques are
  - "Watching the Barn Doors" (application of all available techniques),
  - gas storage observation wells,
  - pump testing techniques,
  - cap rock sealing, and
  - surface monitoring
- Small volumetric release rates can manifest themselves at the surface (crop damage, visible bubbling in streams, water wells, etc.) giving the perception of a very significant leak.
- Pressure–volume, reservoir-simulation, and volumetric inventory verification techniques are not always precise enough to identify vertical gas migration during early stages (possibly years) of gas storage.

RECOMMENDATIONS

The geologic CO_2 storage industry should:

1. Further the "science of observation wells" through additional research.
2. Investigate the integration of new seismic, well steering, and fluid control technologies to pinpoint, locate, and seal a geologic leak.
3. Investigate the design of a custom test for field integrity based on gas storage industry pump testing (high rates of fluid withdrawal while monitoring pressure) techniques.
4. The CO_2 storage industry should heed the caution directed at the gas storage industry during its infancy: "Caution must be exercised in claiming that gas will never be found outside the intended area" [3].

ACKNOWLEDGEMENTS

The author and Gas Technology Institute would like to thank the Research Council of Norway/Klimatek, Statoil, and the Carbon Capture Project (CCP) for funding support of this project. Many gas storage companies in the United States, Europe, and Canada participated in the study by responding to surveys, providing data and offering advice and suggestions through personal communications. Their contributions were invaluable and much appreciated. I would like to thank the reviewers of the document for their recommendations and valuable edits. Finally, the editors of the publication deserve special recognition for their foresight and efforts in compiling information on a timely and important topic.

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