CO_2 Applications

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In my view, carbon capture and storage* (CCS) will provide a significant global contribution to help mitigate climate change. However, the magnitude and timing of the contribution CCS can depend on several factors.

Making Action on Climate Change More Urgent. While the science linking global warming with manmade CO_2 emissions is clear, the pace of national and international political agreements for action requires time. As such, the framework for a post-Kyoto agreement is still unclear. While it is likely such an agreement will be reached, the exact nature will drive the level of urgency on climate-change action.

Creating a Commercial Value for Carbon. The key to action in a commercially driven world is a valid cost on CO_2 emissions. While a CO_2 tax provides a predictable cost for industry, it does not provide governments with clear emissions-reduction levels. Conversely, CO_2 cap-and-trade systems can provide governments with clearer emissions-reduction levels, but they leave industry with uncertain carbon prices. Therefore, industry often "favors" a tax-based approach and governments favor a cap-and-trade approach. The challenge for CCS is to have a sufficiently high price to justify the major capital investment. Experience indicates that the cap-and-trade approach takes many years to introduce and many additional years to adjust caps to create a market price that could justify investment in CCS.

Establishing Early Uptake of CCS. Long-term investments in CCS are hampered by the lack of long-term political agreements and an appropriate carbon price, as outlined above. Early uptake of CCS, however, is required to prove the technology and ensure that supporting legislation can be put in place. Several projects are in advanced stages of engineering in Europe, the US, and Australia. Making these projects happen is crucial. With such early action, CCS has the potential to mitigate global CO_2 emissions by 28% or more by 2050. JPT

*CCS involves capturing flue-gas CO_2, initially from large point sources such as power stations, and compressing the CO_2 for transport before injecting it into the deep subsurface for indefinite storage. Most of the technologies required are available, but not all have been implemented commercially at the required scale. The situation is different for most currently operating projects, which involve separating CO_2 from produced methane and then reinjecting that CO_2 for long-term storage.

CO_2 Applications additional reading available at the SPE eLibrary: www.spe.org.

SPE 108924 • *"Geoengineering and Economic Assessment of a Potential Carbon-Capture-and-Storage Site in Southeast Queensland, Australia" by Y. Cinar, University of New South Wales, et al.*

SPE 114028 • *"CO_2 Storage in Low-Permeability Formations" by Y. Cinar, University of New South Wales, et al.*

SPE 108540 • *"Simulations for CO_2-Injection Projects With Compositional Simulator" by S. Hurter, SPE, Schlumberger Carbon Services, et al.*

EU Policy Options for Regulating Carbon Capture and Storage

Carbon capture and storage (CCS) represents a potentially useful tool to enable the European Union (EU) to manage its emissions of carbon dioxide (CO_2) as it transitions from a fossil-fuel to a renewables energy strategy. The full-length paper examines the regulatory requirements for effective operation of CCS by identifying the issues and risks associated with the capture, transport, and storage of CO_2, and reviews the regulatory options available and their applicability to the operation, management, and control of CCS.

Introduction

CCS is a widely recognized opportunity to enable EU member states to lower emissions of CO_2 by the capture of carbon from large-scale emitters (e.g., power stations) and provide for the long-term, safe storage of this material in underground reservoirs. The EU has set targets for member states to reduce their total volume of CO_2 emissions by 20% of 1990 levels by the year 2020. Achieving these targets in the time scales involved by reducing overall energy consumption or by transferring generation capacity to noncarbon-emitting alternatives is not a feasible option, and, therefore, alternatives must be sought.

This article, written by Assistant Technology Editor Karen Bybee, contains highlights of paper SPE 111824, "Policy Options in the EU for Regulating Carbon Capture and Storage," by ***David J. Williamson*** *and* ***Paul Zakkour,*** *Environmental Resources Management Ltd., originally prepared for the 2008 SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, Nice, France, 15–17 April. The paper has not been peer reviewed.*

While the EU will seek to provide a legislative framework that will enable and encourage the development of the infrastructure required to operate CCS effectively across its sphere of influence, there are particular challenges to be faced in drafting policy and regulation related to the unique nature of the CCS process.

Approach

The CCS process must be described and reviewed to outline the various technical tasks that must be carried out to achieve the goals of the process. In this case, there are three main areas that must be reviewed:

- CO_2 capture.
- CO_2 transport.
- CO_2 storage.

Each of these parts of the process represents varying health, safety, and environmental (HSE) risk profiles. Each of these areas has regulatory analogs in which similar or related processes are subject to current EU and member-state regulation.

CO_2 Capture

The main risks and issues requiring regulation with respect to CO_2 capture include the following.

- The energy "penalty" associated with the additional power requirements needed by the installation to facilitate the capture process.
- The generation of large volumes of CO_2 under high pressures.
- Emissions trading related to the "nonemission" of CO_2.
- Off-site transfer of CO_2.
- Discharges that will change in their chemical composition as a result of the removal of CO_2 and in their total volume related to the energy penalty.

Large Volumes of CO_2. It is evident that the carbon-capture process will generate large volumes of gas under high pressure and low temperatures. Current EU legislation governing such materials is focused in the Seveso II Directive. Annex I Part 1 of the Directive lists "named substances" to which the Directive applies, and currently, CO_2 is not included in the list. Therefore, to include CO_2 under the control of this Directive, the list will have to be amended. There is the potential, however, for this amendment to have unintended consequences for other industrial practices that result in carbon emissions, and, therefore, any amendment should include designations as to the source, temperature, pressure, and quantity of the gas to limit these consequences.

Off-Site Transfer of CO_2. The legislative control on the transfer of CO_2 is dependent on whether the gas is considered as "waste." This also has particular impact on the transport and storage issues. With regard to off-site transfer, issues exist around the reporting of the transport for the purposes of compiling pollutant inventories; whether transfer notifications are required if the carbon is considered to be waste; and what additional regulatory issues may attach to the process should the waste be classed as hazardous. Currently, there is no legislation that specifically relates to the transfer of CCS-derived materials.

If CO_2 captured during the CCS process is classified as waste, then the waste-management legislation under EU law will apply. The principal burden of this legislation applies to those operators receiving waste.

The authorization requirements include notification to the relevant authorities in both the territory generating the waste and that territory receiving the waste. This notification takes the form of a consignment note that provides

For a limited time, the full-length paper is available free to SPE members at ***www.spe.org/jpt.***

full details of the nature of the waste, its source, the control measures taken to minimize the risks associated with the transport, and the arrangements for routing and for insurance against damage to third parties.

Other legislation that may be applicable includes the Integrated Pollution Prevention and Control (IPPC) Directive that requires that any permit include suitable mechanisms to monitor and inventory potential hazardous-material releases. Therefore, should IPPC apply, then the volumes of CO_2 generated and transferred off site would be required to be reported to the competent authority to demonstrate effective control of releases. There remains, however, ambiguity around the classification of CO_2 as a waste, and without this classification, the utility of the regulations listed is questionable.

Discharges. Removal of CO_2 from flue gases results in an increase in the concentrations of other waste gases. Specific emission limits have been set for a number of gases, and the removal of CO_2 from these flue streams may impact license conditions. The wider air-quality objectives of the EU state that member states shall control their emissions to within stipulated limits by 2010. The fuel penalty issues with regard to CCS may, therefore, affect the performance of a member state with regard to this objective.

CO_2 Transport

The transport of captured CO_2 to the final storage site may occur by pipelines, ships, road, or rail. The major issues regarding the transport of CO_2 relating to HSE include the following.

- Routing and signage.
- Transboundary shipments.
- Emissions monitoring.
- Technical standards.

It is obvious that all of these issues already are regulated in the context of the transportation of hydrocarbon products, including natural gas. It is clear that amendments to definitions in existing legislation would represent the preferred option in this case.

The routing of pipelines or other transport corridors presents a risk to surrounding communities and the environment in the event of leaks. Local human and environmental factors will need to be assessed during the route-selection process. Appropriate signage also will be required to alert the local population of the hazard associated with the route. Regarding community risk, the current Seveso II Directive does not apply to the transport of dangerous substances in pipelines. Additionally, CO_2 is not listed as a named substance under this Directive.

CO_2 Storage

The fundamental issue in relation to the storage of captured carbon relates to the legal ambiguity around the status of CO_2 in EU law with respect to its classification (or not) as waste. Considering the life cycle of the CO_2-storage process, a number of distinct phases can be determined for which analogous legislation can be reviewed. These phases include:

- Planning.
- Operation.
- Decommissioning.
- Stewardship and liability.

Site Selection. Site selection is the most crucial element of the planning process for CCS activities. A risk-based approach to site selection is a prerequisite to mitigate the potential hazards to local populations and the environment, in addition to the global risk associated with CO_2 emissions.

A regulatory approach to review of site-selection issues would be to require submission of evidence about a number of key risk issues, including:

- Integrity of the storage-site seal. Structural traps must be assessed in terms of caprock sealing, integrity as affected by issues such as fracture and failure strength, and fluid-flow characteristics, for example.
- Migration pathways or bridges. Assessment of the potential for fluid flow to the surface or nontarget formations must be considered.
- Secondary containment. Given the inherent uncertainty in assessing subsurface-formation characteristics, it is important to assess what secondary containment features may be present and determine how such elements could be included in the long-term storage design.
- Receptors for released CO_2. The environmental baseline study would identify such elements.
- Reservoir-simulation modeling. Predictive modeling is required to evaluate the potential behavior of the injected CO_2 plume. This modeling should include the planned and potential injection rates and the potential pressures that will be generated. The objective of the modeling is to evaluate the integrity of the storage facility over time. The modeling periods should include the lifetime, the injection phase, and the longer-term storage.
- Subsurface monitoring program. The information collated during the planning phase should provide guidance on the critical locations in the reservoir and the key receptors that should be subject to monitoring.
- Iterative modeling and recalibration.
- Decommissioning. A commitment must be made to ensure that final decommissioning and closure be carried out with the best techniques available at that time.

Consideration of the issues listed above should ensure that site-selection and monitoring requirements outlined in the 2006 IPPC Guidelines for National Greenhouse Gas Inventories are fulfilled.

Decommissioning and Long-Term Stewardship. The decommissioning and aftercare of CO_2-storage sites represent an area where there is a significant legislative gap at present. Legislation will be required to:

- Ensure that site operators are under an obligation in their permit to decommission in a manner that minimizes risks to HSE.
- Ensure that operators are under an obligation to monitor the closed site for a set period and address any environmental damage that arises during that period.
- Ensure that sufficient funds are available to address decommissioning and damage issues in the event of operator insolvency.

It is possible that the above requirements can be met through the current provisions of the Landfill Directive, and this may form the basis of an effective model to address the issues around CO_2-storage facilities. The IPPC Directive requires that sites be returned to a satisfactory state following cessation of activities but does not require the provision of any financial security.

References

IPPC Directive. http://eippcb.jrc.es/pages/Directive. htm.

Seveso II Directive. http://mahbsrv.jrc.it/framework-seveso2-leg-en.html. **JPT**

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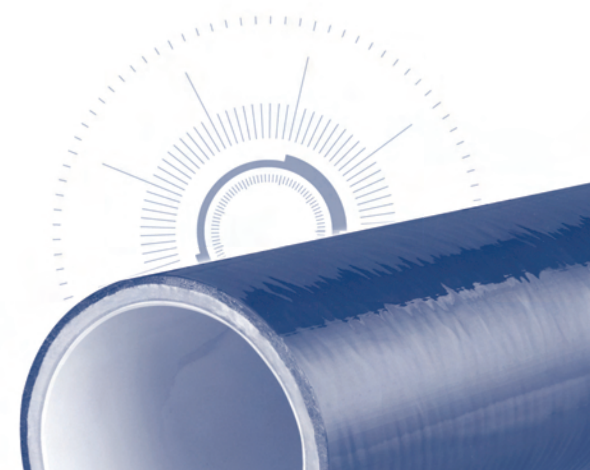

The CO_2 Pilot at Lacq: An Integrated Oxycombustion CO_2-Capture and -Storage Project

In 2006, Total launched an integrated carbon-capture and -storage (CCS) project in southwest France. It entails the conversion of a steam boiler into an oxyfuel combustion unit, with oxygen being used for combustion rather than air to obtain a more-concentrated carbon dioxide (CO_2) stream that is easier to capture. The pilot plant, which will produce some steam for use by other facilities, will emit up to 150,000 tons of CO_2 over a 2-year period, which will be compressed and conveyed by pipeline to a depleted gas field, 8 miles away, where it will be injected into a deep carbonate reservoir. CO_2 injection is scheduled to begin by the end of 2008.

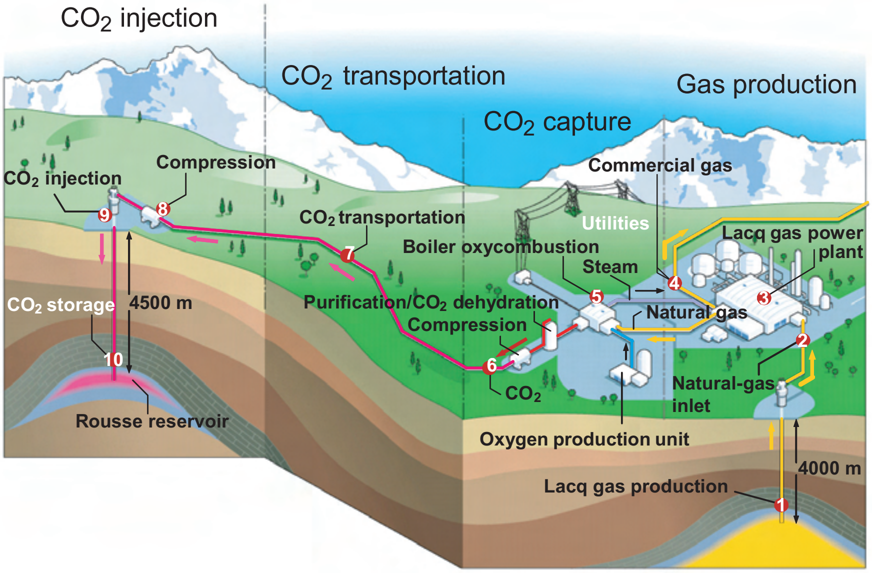

Fig. 1—Lacq CO_2 pilot general scheme.

Introduction

For decades to come, oil and gas will remain an energy source of choice. But oil and gas operators have to develop fields that require much more processing and energy while reducing greenhouse-gas emissions to mitigate climate-change consequences. Among the options, CCS is an important option for tackling greenhouse-gas emissions. While the worldwide CO_2 atmospheric emission was approximately 30 billion tons in 2005, CO_2 geological-storage capacity could be very significant: approximately 600 to 1,200 billion tons in depleted oil and gas fields, 3 to 200 billion tons in unmineable coal seams, and as much as 1,000 to 10,000 billion tons in deep saline formations. This represents 70 to 500 years of storage at current production rates.

Industry pilot plants are necessary to ensure that CCS technology will be reliable, energy efficient, accepted by the public, and commercially viable. At the end of 2006, Total launched an integrated CCS project in southwest France that entails the conversion of a steam boiler into an oxyfuel combustion unit, with oxygen being used for combustion rather than air to obtain a more-concentrated CO_2 stream that is easier to capture. The pilot plant will produce steam for use by other facilities and will emit 150,000 tons of CO_2 over a 2-year period at the Lacq facilities. The CO_2 will be treated, compressed, and conveyed by pipeline to the depleted Rousse gas field 18 miles away to be injected into a deep carbonate reservoir **(Fig. 1).**

The main objectives of the pilot plant currently under construction for startup by the end of 2008 include the following.

- To demonstrate the technical feasibility and reliability of an integrated CO_2 capture, transportation, injection, and storage for steam production.
- To design and operate an oxycombustion retrofitted boiler for CO_2 capture.
- To develop and apply geological-storage qualification methods, monitoring, and verification techniques on a real operational case to prepare for future larger-scale long-term storage projects.

*This article, written by Assistant Technology Editor Karen Bybee, contains highlights of paper IPTC 11737, "The CO_2 Pilot at Lacq: An Integrated Oxycombustion CO_2 Capture and Geological-Storage Project in the South West of France," by **Nicolas Aimard, Marc Lescanne, Gérard Mouronval,** and **Claude Prébende,** Total, originally prepared for the 2007 International Petroleum Technology Conference, Dubai, UAE, 4–6 December. The paper has not been peer reviewed.*

Oxycombustion for CO_2 Capture

The capture and geological storage of CO_2 is a process that consists of separating and recovering the CO_2 from process gases or flue gases at large industrial installations, then transporting it to and injecting it into a suitable underground formation for storage. Of the three main steps in the process (i.e., capture, transport, and storage), the first phase in which the CO_2 is separated from the other constituents (mainly water vapor and nitrogen) of flue gases or other gas stream is by far the most costly, estimated to amount to two-thirds of the overall cost.

According to the type of facilities, CO_2 capture may take place at three different stages: post-combustion, precombustion, or oxycombustion. Each of these techniques is at a different stage of maturity and offers its own advantages and drawbacks. Post-combustion is the most mature, but also the most costly of the three techniques, and is appropriate for existing installations. It involves separating the CO_2 contained in combustion gases usually by means of a liquid solvent such as monoethanol amine. Precombustion yields two separate concentrated streams of hydrogen and CO_2, facilitating CO_2 capture. The process consists of treating the fuel either with steam and air (steam reforming) or with oxygen (partial oxidation) to produce a synthesis gas that contains mainly carbon monoxide (CO) and hydrogen, a potential energy carrier that generates no CO_2 emissions. A second step converts the CO in the presence of water (H_2O) then separates the resulting CO_2 for capture and storage. Oxycombustion is still in the pilot phase. This technique consists of replacing air by oxygen for combustion and therefore yields a combustion gas (or flue gas) highly concentrated in CO_2 (80 to 90 vol%). It also could constitute a suitable retrofit technology for existing installations. Nevertheless, this process requires high-purity oxygen that must be extracted from air, leading to additional energy consumption and indirect CO_2 emissions.

Oxycombustion has been selected for the Lacq pilot on the basis of the possibility to retrofit an existing boiler and the efficiency of this capture technique for large industrial steam boilers. From 2003 to 2005, Total and Air Liquide studied the feasibility of using the oxycombustion of gas and different heavy-oil residues for large steam boilers in a steam-assisted gravity-drainage heavy-oil production scheme associated with CO_2 capture. Those studies and laboratory experiments were sponsored by the French National Agency for Environment and Energy Conservation.

Oxycombustion was compared to a more classical amine unit (post-capture technique) installed on a boiler exhaust for CO_2 capture. When compared on the basis of CO_2 avoided, the oxycombustion process (with 61 units of CO_2 avoided) is superior to the post-capture process (with only 25 units of CO_2 avoided).

Lacq Pilot

Within the existing Lacq gas-treatment complex, an existing boiler built in 1957 within the utilities facilities will be converted into an oxyboiler, with oxygen replacing air for combustion of gas in the first phase and liquid fuel in a second phase. The oxyboiler will produce high-pressure steam (875 psi and 842°F) that will be used as a heating medium or for power generation within the complex. It will be fully integrated into the existing facilities.

A new dedicated cryogenic-distillation air-separation unit will be installed to produce oxygen at a purity varying from 95 to 99.5%. The influence of oxygen purity on combustion parameters will be evaluated to optimize future larger-scale applications. Nitrogen rejected by the air-separation unit will be partially used for CO_2 dehydration-molecular-sieves regeneration.

Flue-gas composition at the boiler exhaust will contain mainly CO_2, water, residual nitrogen, and argon, depending on oxygen purity. The flue gas leaving the boiler at approximately 428°F will be cooled down, and dust and water will be removed. Water dewpoint will be achieved by molecular sieves to avoid any condensation during transportation.

CO_2 Injection

An existing well, RSE1, that has been used to produce wet sour gas since 1972 will be converted into a CO_2 injector. It was selected after cement and corrosion logging that took place at the end of 2006. A workover is planned mid-2008 for the well conversion and installation of the monitoring equipment.

Active and depleted oil or gas reservoirs present many advantages, the most important of which being that these reservoirs are usually reasonably well known and have effective seals. They have already contained hydrocarbons and in some cases H_2S and CO_2. Therefore, the risks of losing formation integrity can be considered as minimal. Geological knowledge has been acquired before their initial development for hydrocarbon production and during the exploitation phase.

The Mano reservoir of the Rousse field where CO_2 will be injected is a deep dolomitic reservoir. Initial pressure was 7,033 psi at a depth of 14,765 ft. The field is now largely depleted with an average downhole pressure of 435 psi. The average downhole temperature is 302°F. Gas produced at Rousse contained up to 4.6% CO_2 and 0.8% H_2S.

An important issue in CO_2-injection projects is the understanding of the long-term geochemical and geomechanical phenomena. It is necessary to demonstrate that the stress modification in and around the reservoir induced by the CO_2 injection, combined with possible chemical modification of the materials, will not affect the structure and damage the caprock seal by creating new fractures or opening existing sealing faults.

Baseline surveys and a monitoring program also are a major part of the CO_2-injection project. Soil-gas mapping at different surface locations is under way. The plan is to take soil samples every 3 months at least a year before injection to identify natural CO_2 emissions from the soil linked to seasons and meteorological conditions.

A microseismic monitoring system also is to be installed to identify possible effects of the CO_2 injection on the reservoir. This system will comprise six microseismic sensors around the injection site installed at an average depth of 328 ft, and three microseismic sensors installed downhole slightly above the top of the reservoir. JPT

A Monitoring and Verification Plan for The Otway CO_2 Pilot Project

The Australian Cooperative Research Center for Greenhouse Gas Technologies (CO_2CRC) currently is injecting 100,000 tons of CO_2 in a large-scale test of storage technology in a pilot project in southeastern Australia called the CO_2CRC Otway Basin Project (Otway). The Otway basin with its natural CO_2 accumulations and many depleted gas fields, offers an appropriate site for such a pilot project. An 80% CO_2 stream is produced from a well near the depleted gas reservoir used for storage. The goal of this pilot project is to demonstrate that CO_2 can be transported and stored underground safely and its behavior tracked and monitored.

Introduction

The commercial oil and gas leases in the Otway basin in Victoria, selected for the pilot project, are in an undeveloped CO_2 field (Buttress), which is the source of CO_2, and a depleted gas reservoir (Naylor), which is the injection/containment site. The extracted and separated CO_2 stream is transported by pipeline and injected into a new well (CRC-1), drilled downdip of the existing well, and into the depleted Waarre reservoir in the Naylor field at a depth of approximately 2000 m. The existing shut-in production well (Naylor-1) is being used as the monitoring well. Characterization of the site has involved the collection of a large quantity of geological, geophysical, and other regionally relevant data and the construction of static and dynamic reservoir models. The regional formations provide an excellent porous and permeable geological formation that provides a highly suitable reservoir system for CO_2 storage. In summary, the site-assessment results, indicating that the Waarre formation is a suitable site for CO_2 storage, conclude the following key attributes of the site. There are no significant faults evident in the wells at the Waarre C level; there is a fairly uniform Waarre C thickness. The local and regional seals have contained a number of natural CO_2 accumulations in the eastern Otway basin over geological time. The storage reservoir has sufficient porosity and permeability to be able to accept the injected CO_2 at forecast rates. The injected CO_2 is predicted to move updip from the injector location and migrate to the crest of the fault block and accumulate below the residual-methane gas cap in the vicinity of the existing Naylor-1 well. The selected site has the major advantage of being onshore rather than offshore, allowing the project research teams to test and further refine the monitoring and verification techniques at a more accessible location.

*This article, written by Assistant Technology Editor Karen Bybee, contains highlights of paper OTC 19202, "Developing a Monitoring and Verification Plan With Reference to the Australian Otway CO_2 Pilot Project," by **Kevin Dodds,** SPE, CSIRO, and **Sandeep Sharma,** SPE, Schlumberger, originally prepared for the 2008 Offshore Technology Conference, Houston, 5–8 May. The paper has not been peer reviewed.*

Monitoring and Verification Role

The goal of a monitoring framework is to provide a comprehensive set of information from direct measurements and remote sensing of the process of injection and storage of CO_2, such that the complete storage process can be documented appropriately to establish the safe transport, injection, and containment of CO_2, and the subsequent safe abandonment and restoration of the site. For the purposes of monitoring and verification, a regulatory framework should

- Provide for the generation of clear, comprehensive, timely, and accurate information that is used to manage environmental, health, safety, and economic risks effectively and responsibly and to ensure that set performance standards are met.
- Determine to an appropriate level of accuracy the quantity, composition, and location of gas captured, transported, injected, and stored and the net abatement of emissions. This should include identification and accounting of fugitive emissions.

The range of monitoring technologies comprises an integrated framework of diverse methods and measurement systems crossing many disciplinary boundaries. These are categorized by their means of measurement: remote sampling, direct sampling, or categorization by domain of operation, of which there are three. The first domain of operation is the subsurface domain, to monitor and verify the deep injection and migration behavior of injected CO_2, from the surface or borehole. The second is the near-surface domain, comprising sampling and remote measurements to verify the nonseepage into shallow zones and soils from surface and borehole. Finally the atmospheric domain, comprising a baseline characterization of seasonal and diurnal variation of existing gas distribution and composition accumulated over suitable time that can be monitored by point-source gas sampling, coupled with dispersion modeling, or by spectral absorption and infrared detectors locally or by aircraft and satellite. The monitoring technologies are deployed in a number of modes across the project lifetime. Monitoring can be categorized into baseline and operational monitoring, while verification monitoring consists of both subsurface and environmental confirmation of performance criteria.

The full-length paper is available for purchase at OnePetro: www.onepetro.org.

Pilot-Project Phasing

The role of monitoring and verification of performance for Phases 1A, 1B, and 2 will require a continuum of high-intensity monitoring activities. The transition from one phase to another will be dependent on well-defined engineering determinants. Phase 2 will see post-injection closure (or sale) of the CO_2-production Buttress well and decommissioning of the surface facilities. Monitoring tasks will be ongoing in the Naylor site to validate the transition criteria to Phase 3. Validation that the plume is stable will come from log-based measurements showing no evidence of CO_2 in the overlying formation beyond secondary containment. In addition, fluid samples collected from existing deep water wells should show no evidence of the injected CO_2. There are four such wells. Soil and air samples collected in the proximity of the monitoring well (Naylor-1) and the injector (CRC-1) well also should show no evidence of the injected CO_2. Phase 3 is focused on public assurance and monitoring for long-term storage security. It is planned to augment an existing program of water-well monitoring by the local water authority with testing of soil samples near these wells for evidence of injected CO_2. If no evidence of the injected CO_2 is detected in 2 years, the project can move into Phase 4. Monitoring for Phase 4 will continue to focus on public assurance through the augmented testing program in the deep wells. When there is no evidence of injected CO_2 for an additional 2 years, this phase can terminate. The project is currently at the beginning of Phase 1B (i.e., production and injection). The injected CO_2 is magmatic in origin and consequently has an isotopic signature quite different from that of CO_2 generated biologically and from fossil fuels, and hence can be detected.

Otway Subsurface Monitoring

The first task was to refine the uncertainties in reservoir properties. There has been a reasonable elapsed time between the original acquisition of 3D seismic and the subsequent production and shut-in of the Naylor-1 well. There is residual gas within the Naylor reservoir, with uncertainty as to the gas/water contact. The presence of residual gas provides a significant challenge to the direct detection of the CO_2 plume by seismic once it migrates out of the injection-well water zone. More-precise understanding of these properties will determine the monitoring options available. Naylor-1 has been re-entered to establish gas/water contacts with reference to a reservoir saturation log and to establish the integrity of the cement bonds through casing- and cement-inspection logs. This provided the opportunity to test the viability of vertical-seismic-profile (VSP) methods. A new injection well (CRC-1) has been drilled within 300 m of the monitoring well (Naylor-1). Data-gathering activities include extensive coring above and through the top seal and reservoir. Openhole wireline logs have been run, and pressure measurements and fluid samples from the reservoir have been taken. Pressure-transient testing has been used to determine the hydrogeologic characteristics before CO_2 injection. The results were used to modify the injection protocol. Cement-inspection logs have evaluated the integrity of the bonding of the cement. Downhole pressure and temperature gauges have been run to monitor injection conditions. Seismic geophysical monitoring for Otway is being carried out in three distinct phases: before injection to establish baseline data, during injection (i.e., between injection and breakthrough), and post-injection for comparison against the baseline-data sets. The baseline data consist of a 3D surface seismic and 3D VSP acquisition. In collaboration with CO_2CRC, Lawrence Berkeley National Laboratories designed and built an integrated seismic and geochemical sampling completion that was installed in the Naylor-1 monitoring well in late 2007. This equipment allows both geochemical and seismic data to be obtained during the injection period.

This completion is designed to provide geochemical sampling at three distinct levels, combined with three types of geophysical-monitoring activities. The geochemical sampling occurs through three sets of U-tubes with inlets above and below the gas contact. There also are two sets of pressure and temperature sensors in these locations. The sampling occurs through one-way valves, and the fluids are lifted by nitrogen to the surface, retaining reservoir conditions. The first seismic activity addressed is an array of geophones at approximately 500 m above the reservoir to provide the means to acquire walkaway data during injection The second is a set of three triaxial geophones within 300 m above the reservoir in an array to monitor for any microseismic events that signal changes in stress state associated with the injection and detect or rule out any signs of reactivation of the bounding fault ahead of time. The third consists of a set of hydrophones and geophones within the reservoir to look at high-resolution travel times and changes associated with the changing fluid level at the monitoring well.

The presence of naturally occurring subsurface CO_2 in the Otway subbasin makes identifying the injected CO_2 more complex. A regional survey of the distribution, type, and origin of existing CO_2 is being carried out through an integrated program of soil-gas sampling, hydrogeology, water chemistry, and atmospheric measurements. Sampling is carried out over a defined grid and repeated several times per year (to account for seasonal effects), before, during, and after injection. The areal consequences of CO_2 migration and trapping are being addressed through characterization of the hydrodynamic properties of the region. The connectivity and fluid-migration time scales of the existing freshwater reservoirs are established with available hydraulic-head, well-pressure, and geological information. This provides input into establishing fluid pathways and flow time scales and identifying flow barriers resulting from facies changes and faults. A sentinel network of atmospheric monitoring equipment has been set up to provide the environmental background against which anomalous sources of CO_2 can be detected.

Conclusion

Otway currently is providing the opportunity to test all phases of a large-scale geosequestration project comprehensively. The project also addresses near-term and long-term monitoring issues raised by the necessary time of containment. This monitoring provides confirmation of performance objectives necessary to move from one phase to the next. The monitoring comprises established technology, but also has provided the opportunity to develop an innovative integrated geochemical and geophysical completion for the monitoring well. A comprehensive program of surface and borehole 3D seismic as baseline has been acquired in anticipation of subsequent time-lapse surveys. Management of the quality of the time-lapse data has been achieved by thorough pretesting for repeatability factors. **JPT**