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Aquistore demonstrates safe and cost-effective CO2 storage

Aquistore is an on-going CO2 measurement, monitoring and verification project to demonstrate that storing carbon dioxide 3.4km deep underground in a brine and sandstone water formation is a safe, workable solution to reduce greenhouse gases.

Located in southeastern Saskatchewan, Canada, the Aquistore project is Canada's first deep saline aquifer carbon dioxide (CO2) storage project. It began injection in February of 2015, and has safely stored over 300,000 tonnes of CO2 from SaskPower's Boundary Dam Carbon Capture Facility. At the time of its commissioning in 2014, Boundary Dam represented the world's first commercial post-combustion CO2 capture from a coal-fired power plant.

The Aquistore project began its development in 2009, well before construction on the Boundary Dam Capture Facility began. Initial plans for deep geological storage were devised by the Petroleum Technology Research Centre (PTRC) – a not-for-profit research company based in Regina, Saskatchewan – and early planning considered different industrial CO2 sources. The capture scenarios from different industrial sources in Saskatchewan were initially driven by new provincial and federal emissions regulations being developed with the aim of reducing Saskatchewan's greenhouse gas emissions to 2005 levels by 2030.

The province is blessed with just the right geology for deep geological storage of CO2, and has a perfect reservoir in the Deadwood Formation that ranges from3400 metres deep in the province's southeast to 2200 metres in the Regina area. It was this formation that was chosen as the proposed target formation in the early stages of the project.

In 2009 PTRC established Aquistore's Scientific and Engineering Research Committee (SERC) to identify and characterize a target storage formation, conduct a risk assessment, develop the research program, and define a public outreach/consultation plan. PTRC had a significant knowledge base for CO2 geological storage research, having managed the Weyburn-Midale CO2 Monitoring and Storage Project beginning in 2000. The SERC for Aquistore utilized many of the lead researchers from the Weyburn-Midale project in the design and management of its program.

Value	Health & Safety	Environment	Financial	Schedule	Reservoir Suitability	Storage Security	Capacity Building	Societal Acceptance
Goal	No lost days due to health or safety incidents.	No adverse environmental impacts.	Execute the project within budget (financial).	Maintain project schedule	Demonstrate CO_2 injection into a deep saline formation, at rates and in volumes sufficient for a large industrial CO_2 source.	Demonstrate containment of injected CO_2.	Build industrial ability to conduct CCS by conducting and disseminating industry-leading research.	Public education and consultation leading to project support.

Table 1. Aquistore project values

Funding was secured from different sources, including cash and in-kind support from levels of government and private sector partners.

In 2011, PTRC settled on the source of CO2 for Aquistore when the government-owned power utility, SaskPower, went forward with carbon capture on a 150MW coal-fired turbine at Boundary Dam Power Station. The company received over 250 million dollars (CND) from the Government of Canada to offset some of the eventual 1.5 billion dollar cost to retrofit the plant (the cost represented the combination of a new turbine -- $600 MM – and post-combustion capture ($900 MM). Construction lasted from 2011 to 2014.

Risk assessment

After determining Boundary Dam as the source, PTRC worked with SaskPower to establish a location for the CO2 injection and observation wells, which were proposed for SaskPower's land just 3 km from the capture facility. In 2011, the SERC developed a risk assessment plan that was enacted prior to the start of drilling and the implementation of appropriate monitoring and measurement technologies.

Analyzing risk reduces the likelihood of a project's failure – both from technical issues and public perception – and helps mitigate the severity of any possible challenges. A proper risk assessment is critical ahead of project execution, instills confidence from external stakeholders and allows for an efficient application of project resources.

Effective risk management includes proper geologic characterization of the injection location and surrounding area, deciding on an effective monitoring program, and creating an interactive communications and public outreach plan.

At Aquistore, a "Feature, Event and Process (FEP)" risk evaluation was performed, based on the severity and likelihood of specifically identified events, and then scaled on a risk matrix. The following were the four stages of the risk assessment conducted:

• Stage one built a project value matrix, identified project relevant FEPs, and identified key experts to contribute to the risk assessment.

• Stage two was a workshop to discuss and evaluate the likelihood and severity of selected FEPs.

• Stage three involved FEP ranking – concrete risk scenarios were identified, and the likelihood and severity of risks were evaluated.

Finally, actions were identified to reduce or eliminate the impact of FEPs, which in turn resulted in a comprehensive measurement, monitoring and verification program and an effective public outreach plan. Table 1 shows the values that emerged from the risk assessment process.

Public consultation and engagement

Aquistore held its first public open house in the community of Estevan, Saskatchewan –

near the Boundary Dam facility and proposed well locations – in May of 2012. The public consultation was ahead of the commencement of the drilling of the observation and injection wells, allowing residents to offer feedback and voice concerns about project risks and well locations. The open house was well advertised – including flyers delivered door-to-door – and over 100 residents attended.

Additional feedback was provided before the open house via one-on-one meetings with local landowners most directly affected by the wells near their properties. An additional feature of the outreach and engagement plan was informational presentations to local chambers of commerce, Estevan city council and other community/political leaders.

Figure 1. The first Aquistore public open house occurred in Estevan in May, 2012, with information stations about the project's wells, proposed MMV, and capture source

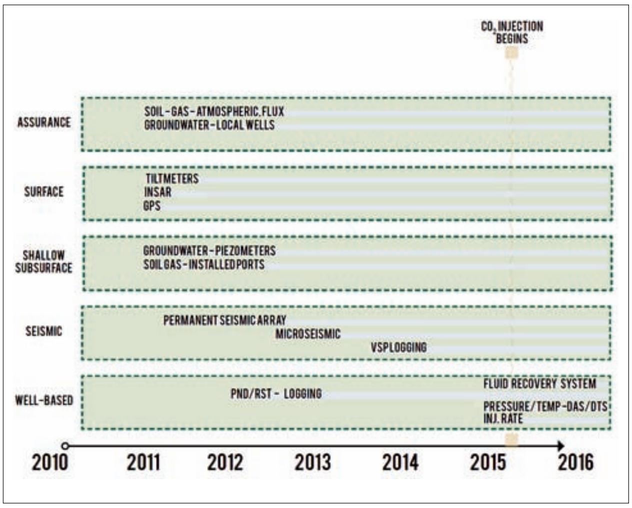

Table 2. Aquistore monitoring, measurement and verification program as developed before injection of CO2 began in 2015

Drilling and completion of the wells

In the summer of 2012, the wells were drilled for the Aquistore program. The target zone for injection was the Deadwood Formation, the deepest and oldest sedimentary unit throughout the province. It is Cambrian in age, and is an interbedded mix of high porosity sandstone/shale filled with a dense, hot salty brine. First, the injection well was drilled to a depth of 3396m, making it, at the time, the deepest well drilled in the Province of Saskatchewan. Cores were taken from the caprock zone, called the "Icebox Shale" and from further down in the Deadwood reservoir.

The "deepest well in the province" record was broken later that summer, when the observation well was drilled to 3400m. The observation well is located 150m to the north of the injection well.

The injection well was completed first with casing to the bottom of the well and tubing to allow for CO2 injection, then perforated in the target Deadwood porous zones. Pressure gauges and fibre optic lines to carry pressure and temperature data were installed on the tubing and casing.

The observation well saw only casing to total depth, but also included fibre optic and fluid sampling lines run on the outside of casing. The observation well itself has never been perforated and remains isolated from the reservoir. This allows for various logging and other measurement tools to be run in the well to monitor injection performance.

Measurement, monitoring and verification program

As a result of the risk assessment, Aquistore undertook the development of a rigorous measurement, monitoring and verification (MMV) program ahead of CO2 injection to assure the safety and effectiveness of operations (see list of MMV in Table 2). The Aquistore site constitutes the largest field laboratory in the world for the study of CO2 injection and storage at an industrial scale. What follows is a description of the scientific measurement procedures and equipment in place that is assuring the safety and security of long term storage.

Surface Monitoring

Aquistore's surface monitoring equipment includes ground water well and soil-gas sampling wells, piezometers to measure well water pressures, and three surface deformation measurement technologies:

• GPS

• Interferometric Synthetic Aperture Radar (InSAR) reflectors;

• Tiltmeters to measure shifts due to CO2 fluid injection or natural land deformation as compared to the earth's seasons, tides, or rainfall.

InSAR and GPS collect data by satellite to monitor earth surface deformation with a precision of a few mm/year and also to assess whether there are changes attributable to CO2 injection and storage. Eight dedicated GPS stations provide a stationary reference location for tiltmeter and InSAR systems. Tiltmeters monitor extremely small changes in inclination of the ground surface resulting from subsurface activities such as CO2 injection.

The tiltmeter array consists of six high-resolu-

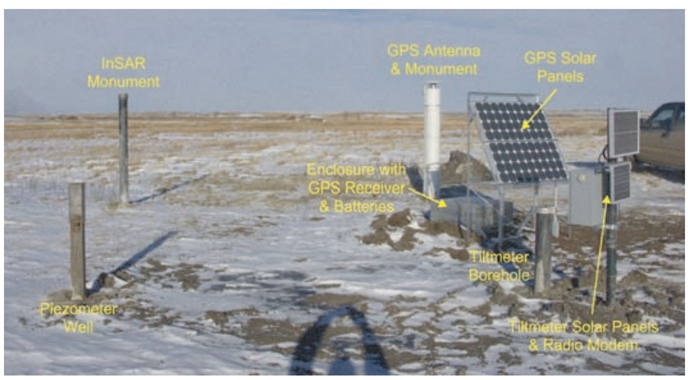

Figure 2. An Aquistore superstation showing surface instruments from different surveillance systems

tion surface meters with 15 m cables, 5-Watt solar panels and rechargeable batteries. See Figure 2 for the arrangement of these surface MMV in one of several locations at Aquistore.

Baselines of all these technologies' measurements were undertaken prior to the start of CO2 injection. Physical and chemical data have continued to be collected from 21 groundwater wells and 49 soil gas monitoring wells at the site.

The sampling program is intended to monitor any potential changes in the baseline groundwater and soil gas chemistry since the start of CO2 injection. The soil gas sampling is a biannual practice and groundwater samples are collected annually from both domestic and project water wells.

Permanent Geophone Array and Passive Seismic Monitoring

A permanent array of 645 geophones was installed to collect seismic data and assist in monitoring the injected CO2 plume (See Figure 3). There are two sets of geophones within the array. Most of the 645 are charged up only during seismic shoots and measure the returning waves coming back up from the Deadwood formation as set off by vibroseis vehicles or dynamite charges. These seismic imaging shoots occur only when CO2 totals injected into the Deadwood formation reach certain milestones.

The data from the geophones helps create deep subsurface images and help locate the plume in the reservoir to show how it has changed shape and location (See Figure 4). These images are also compared to simulations done by researchers to makes sure the CO2 is acting in conformance with the expectations from those models.

A further number of these geophones have been placed 20 meters deep in the ground (in a north, south, east, and west cross shape) and are collecting data for continuous passive seismic monitoring.

Passive seismic allows Aquistore to differentiate sources of subsurface seismic activity, whether they are naturally occurring, induced by the project, or sourced from other industrial processes nearby. Passive seismic data is collected not just from the geophones, but via fibre optic technologies downhole.

Five broadband stations that consist of seismometers and recorders integrate the data from the geophones and fibre optic lines. To date the passive seismic monitoring at Aquistore has not recorded any induced seismicity due to the injection of CO2 although local and farther afield events (natural earthquakes) have been detected

Figure 3. Aquistore's permanent seismic array of 645 geophone locations (blue dots), within a 2.5 km square zone indicated in orange. Theinjection and observation wells are indicated in the centre of the blue dots

Fibre Optics for Seismic Imaging and Other Monitoring

At Aquistore, fibre optics are being used for seismic sensing. There are two kilometres of distributed acoustic sensing fibre optic cables trenched about a meter deep in the ground and one fibre optic cable cemented behind the casing down the observation well to a depth of 2800 meters (see Figure 5). Distributed acoustic sensing (DAS) as a method of data collection is a routine practice at Aquistore, and DAS data and geophone-based seismic data complement one another and provide more in-depth analysis of the CO2 location in the subsurface.

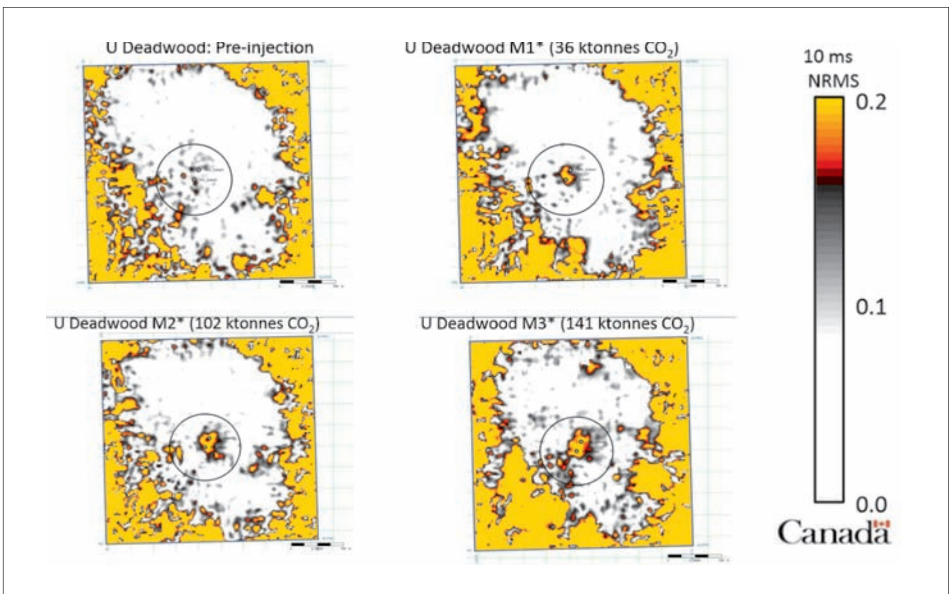

Figure 4. Seismic images of Aquistore's injected CO2 in the Deadwood formation, taken prior to injection, at 36 kt, 102 kt, and 141 kt. The injection and observation wells are indicated with dots inside the circled area. Image from Geological Survey of Canada

Observation Well MMV Tools

Aquistore's observation well is used to monitor different aspects of the CO2 injection activity, and aside from a downhole DAS fibre optic cable there are other downhole gauges, such as a fluid sampling. The fluid recovery system (FRS) developed at the University of Alberta was commissioned at Aquistore prior to first injection of CO2. This system was permanently installed to a depth of 3200m.

The FRS had been designed to allow reservoir fluids to be sampled at depth and brought to the surface preserved under "in-situ" conditions. The samples provided valuable insight into the conditions of the reservoir as it was impacted by the injected CO2, giving a better understanding of subsurface fluid phase behaviour and predicting plume migration and behavior.

For the first three years of the Aquistore project, the FRS performed satisfactorily and was valuable in assessing and confirming the presence of CO_2 at the observation well. Over time, as the plume inundated the Deadwood with CO_2, the FRS was less useful since the presence and concentration of CO_2 in the vicinity of the observation well was well-known.

Since pressure sensors in the observation well were damaged and had become inoperable, it was felt the project needed to regain measurement of formation pressure away from the injector. The decision was made to convert the FRS into a bubble tube pressure monitoring system. This has allowed for the measurement of pressures in the observation well, and the stream of data from this new unit has been useful in seeing the pressure transients between the two wells as CO_2 injection ramps up and down. The data obtained helps numerical simulation, and prediction of the position of the CO_2 plume.

Additional Plume Monitoring Technologies

Utilizing both wells' downhole instrumentation, borehole gravity (BHG) technology has been integrated to detect changes in the gravity field near the injection and observation wells throughout the life of the project. The changes in density, which are caused by changes in mass surrounding a well, vary according to shape and size of the CO_2 plume. The changes in the gravity field are detected by time-lapse borehole gravity surveys run as the CO_2 injection progresses.

Aquistore has also deployed time-lapse pulsed neutron decay (PND) technology in the observation well to track CO_2 saturation changes in the reservoir and to monitor the cemented casing-borehole annulus for evidence of vertical migration of CO_2. For mechanical integrity monitoring, PND is most effective when used as a time-lapse measurement comparing a base pass to subsequent monitoring passes. Since the commencement of the project 17 PND surveys have been conducted at Aquistore.

Electromagnetic data has also been collected at Aquistore to provide information about regions within the reservoir with different resistivity. Resistivity data is collected utilizing a downhole casing source (a deep electrode at storage formation depth), a top casing source (a clamp on the wellhead), and surface electrodes – all are then compared to baseline resistivity measurements. The goal of electromagnetic studies is to use the data, along with information obtained from other technologies (e.g. gravity, seismic, PND), to feed sophisticated models that generate two-dimensional maps showing the location of the CO_2 plume.

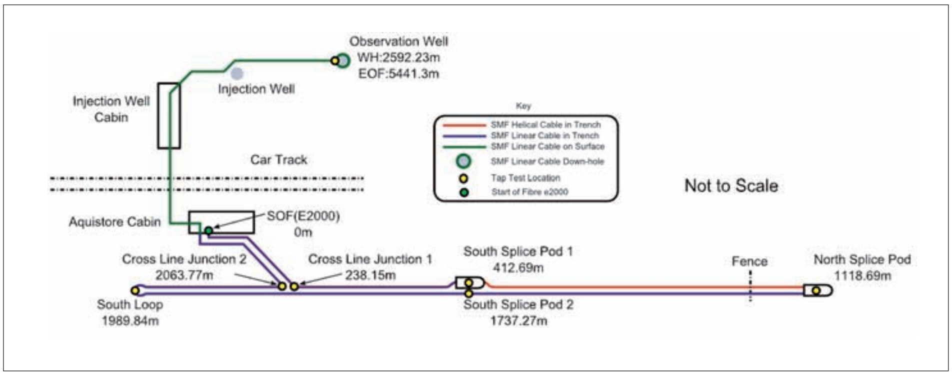

Figure 5. Aquistore fibre optic cable layout

Discussion of Results and Learnings Thus Far

While lessons were learned early on about bringing a project of this type to reality, the more important findings now are from its operations. Specific challenges, such as the intermittent CO_2 supply (both because of capture plant maintenance and the reality that most of the CO_2 is sold for enhanced oil recovery to Weyburn) affected well operations early on. The intermittent supply led to strange and interesting transient pressure changes, changes that detected a leak in the tubing string long before it became impactful. It was readily mitigated.

Operational activities have also given rise to the impact of geochemical phenomena that have been traced, imaged, and modelled. The brine in the Deadwood is 300,000 ppm chlorides, which have interesting effects when subjected to pressure and temperature changes due to injection.

In monitoring, the conversation has turned from doing everything possible that the budget and imaginations allow, to paring measurement and monitoring down to the minimum. The minimum represents what would allow for safe operation of the well, monitoring of the plume, and detecting any leaks, while maintaining public confidence.

This may lead the project more towards fibre optic seismic imaging over the cost and maintenance of the permanent array, and may lead away from soil gas/ground water monitoring, opting instead for earlier leak detection. The goal is to decrease costs incurred by future CCS storage projects, while at the same time maintaining security of storage and public confidence in the process.

All of the monitoring systems, along with the well itself, generate massive streams of data, as granular or as general as is desired. Second-by-second data, or monthly averages, can be gleaned from all of the systems on site. This allows for a steady stream of data to be incorporated into models and simulations of on-site processes to help determine best courses of action, or to predict CO_2 behaviour under certain conditions. This type of data analyses is only available to working projects that have actual injection, but can be applied more broadly to CCS projects elsewhere that are more conceptual.

Future of Aquistore

The PTRC, along with the SERC and partners in the Aquistore program, are excited for what is coming for Aquistore:

- Continued investigation in cheaper and better methods of seismic plume imaging is ongoing. Minimizing the monitoring datasets is important work in demonstrating reduced costs for CCS worldwide.

- A manual of "regular industrial operations" of a CCS site, due in 2022.

- New modelling that includes more reservoir properties and processes, with an emphasis on geochemical reactions in the near-wellbore.

- Temperature effects on the geomechanics of the reservoir, arising from cooler CO_2 hitting the warmer reservoir, is important work to explain some interesting injection phenomena related to intermittency.

• Linking the Aquistore well to a nearby deep circulation geothermal project to attain more reservoir attribute data.

• Investigating the use of deeply circulated CO2 as a geothermal carrier.

• Looking into the placement and design of a 3rd well in the Aquistore program. A well that will begin life as a monitoring station, but be converted to an injector later. This will speak to the ultimate capacity of the Deadwood reservoir in the region, and what magnitude of CCS we can reasonable expect to install.

Ultimately, the future of CCS in Canada, and internationally, will need to be driven by proper policy and regulatory development. Aquistore and the Weyburn oilfield – which also receives CO2 from Boundary Dam for enhanced oil recovery – are located very close to the United States, and the Weyburn field also receives CO2 via pipeline from the Dakota Gasification Company's facility in Beulah, North Dakota.

This raises interesting questions for both the United States and Canada related to carbon credits and tax incentives that have already been put in place in the US (45Q) but which do not have direct application as a motivating factor for creating more capture facilities for its northern neighbor.

With the possibility of trans-border transport of CO2 already a reality in the case of DGC and Weyburn, questions about credits for storing CO2 in a foreign jurisdiction raises interesting possibilities for development of policies and incentives on both sides of the border that will further advance CCS projects. If Aquistore and its success at demonstrating the safety of storage advances the CCS cause by bringing down storage costs and demonstrating minimum monitoring requirements, the project will have attained many of its goals.

More information

For more information on becoming a partner in the research at Aquistore, contact the PTRC at **info@ptrc.ca**. Follow the latest research results by following the company on twitter **@ptrc_sk**