Aquistore: Year One – Injection, Data, Results

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Abstract

Aquistore is an independent research project managed by the PTRC demonstrating the storage of carbon dioxide (CO\textsubscript{2}) deep underground in a brine sandstone formation. Results from the baseline MMV program are compared with measurements after the injection of 36,000 tonnes of CO\textsubscript{2}. Surface seismic results indicated excellent repeatability with baseline surveys; the data achieved a global NRMS of 10\%, allowing for the detection of small amounts of CO\textsubscript{2} at significant depths. Passive seismic monitoring detected no injection-induced seismicity. Post-injection groundwater and soil gas sampling was relatively unchanged, and indicate there are no signs of seepage of CO\textsubscript{2} at the site.

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1. Introduction

The Aquistore Project is Canada’s first deep saline CO$_2$ storage project. An integral part of SaskPower’s Boundary Dam Carbon Capture and Storage (CCS) Demonstration Project, Aquistore is the ‘S’ (storage) component in the Boundary Dam project. With over $17M of scientific monitoring installations and $45M of cash and in-kind funding, the Aquistore project is providing regulators and governments with the science-based facts and information necessary to develop informed policy and legislation.

The project’s measurement, monitoring, and verification (MMV) program, reviewed and discussed here, includes surface, shallow subsurface, downhole, and seismic monitoring. Unique installations include a down-hole Fluid Recovery System (FRS) in the project’s observation well capable of recovering fluid samples from over 3 km underground. In addition, distributed temperature sensing (DTS fibre optic lines) in both the injection and monitoring wells are measuring subsurface temperatures. 3D seismic images of the injected CO$_2$ have been attained through several methods, including from a permanent array of 650 surface geophones, a vertical seismic profile (VSP), and distributed acoustic sensing (DAS) lines. In addition, electromagnetic surveys, well logs, and various assurance monitoring programs (groundwater, soil gas, atmospheric, microseismic, surface deformation) have been underway at Aquistore since 2012 (pre-injection), and are offering baseline data for comparison with results recorded in the past year since injection began. Results from the pre-injection MMV program are compared to those with measurements after the injection of 36,000 tonnes (36 kt) at the end of February 2016. Through this comparison of pre- and post-injection results, some preliminary comments will be made on the efficacy of different MMV methods at this, the project’s early stages, and some observations offered on the additional program research needed going forward.

2. Background

Aquistore is the buffer storage location for the Boundary Dam Integrated Carbon Capture and Storage Facility, located near the city of Estevan in southeastern Saskatchewan. The coal-fired Unit 3 turbine at Boundary Dam produces 150 MW of power (110 MW net, after allowing for parasitic load for the CCS and associated infrastructure) and in 2015 the facility captured approximately 400 kt of CO$_2$, and is on target in 2016 to capture over 800 kt. The majority of the CO$_2$ produced is shipped via a 66 km pipeline to Cenovus Energy’s Weyburn oilfield for enhanced oil recovery. The Aquistore injection well has been receiving variable amounts of CO$_2$ – depending on the CO$_2$ requirements of the Weyburn field – since April 2015. Since January 2016, Aquistore has on average injected ~400 t/day, and as of September 2016 a cumulative total of 88 kt had been stored in the reservoir.

The Aquistore field test site contains a number of measurement and monitoring systems. Figure 1 offers an aerial map of the site, with Boundary Dam Power Station on the right of the photo, and the CO$_2$ pipeline route in blue running to the north of the Aquistore wells and then south. Blue dots represent the location of geophones in the permanent seismic array around the injection and observations wells, which are illustrated in the centre of the array with two red dots (injection to the south, observation to the north). The teal triangles around the site represent “super stations” containing a number of MMV systems, and the green circles represent soil gas sampling locations.
A complete overview of the various MMV technologies and baseline studies done at the Aquistore site prior to when injection began in 2015 may be found elsewhere [1], however an overview of the equipment at the site is useful ahead of some discussion of MMV results recorded since injection began. Equipment includes:

- **Injection and Observation Wells**: the two deepest wells ever drilled in Saskatchewan, the Aquistore injection well (Figure 2 – total depth 3396 metres) and observation well (Figure 3 – total depth 3400 metres) are both completed with various measurement and monitoring technologies. These include digital temperature sensing (DTS) lines and a distributed acoustic sensing (DAS) line to provide highly accurate and repeatable seismic measurements using fibre optic technology. The observation well also includes a fluid recovery system (FRS) which allows for reservoir fluid sampling, and casing-conveyed pressure gauges at different levels to measure pressure due to CO₂ injection.

- **Permanent Seismic Array**: 630 geophones were installed in 2012 at a depth of 20 m, and another 30 three-component geophones were added in 2013. Seismic surveys have included both vibroseis and dynamite shots as sources, with the first post-injection survey completed in February 2016. The permanent array also allows for continuous passive seismic monitoring of the site for any induced seismicity that might happen due to injection. As of summer 2016, no induced seismicity has been recorded.
Figure 2. Aquistore’s injection well. Geological formation on the left, with well equipment and description on right.

Figure 3. Aquistore’s observation well.
Surface-based MMV Program: Aquistore has a number of monitoring systems on the surface and shallow subsurface. Many of these are grouped in near proximity to each other at 13 different locations within the 5km by 5km grid around the injection and observation wells. Tilt meters, InSAR devices and global positioning systems (GPS) as well as ground water sampling wells are included at these locations (see Figure 4). In addition, 50 semi-permanent soil gas probes were installed at a depth of one and two metres at locations around the site. The ground water sampling program consists of 40 wells which were sampled at the site and in the wider vicinity around it, including many pre-existing domestic and industrial sites. These included 19 dedicated wells of between 2 and 42 metres in depth that were drilled by the project to acquire baseline readings prior to the injection of CO$_2$ and which have continued to be sampled after injection began.

![InSAR Reflector, GPS Receiver, Groundwater Wells, Solar Power, Tiltmeter, Seismometer](image)

Figure 4. Aquistore MMV (“super”) station, with devices indicated.

3. Experimental and Discussion

3.1. 3D Time Lapse Seismic Results

In February 2016, three simultaneous seismic surveys were completed to image the subsurface – utilizing the permanent seismic array (see Roach et al. and White et al.) [2,3], downhole geophones in the observation well, and the casing conveyed distributed acoustic sensing (DAS) fiber optic line on the observation well (see Harris et al. and Miller et al.) [4,5]. The goals were to examine whether one or another of these systems were more effective at imaging the CO$_2$. The comparison between the baseline seismic measurements and those conducted in February 2016 show an anomaly was located in the Upper Deadwood formation. The anomaly at the injection well stretches towards but does not reach the observation well (see Roach et al. and White et al., this issue) [6,7]. See Figure 5.

Based on data observed, the anomaly likely corresponds to 18 kt of the injected CO$_2$. CO$_2$ levels in the Black Island formation above the Upper Deadwood, and levels in the Lower Deadwood are both considered to be below the seismic detection threshold and were not clearly observed.
The project has also compared the capabilities of the distributed acoustic sensing line (DAS), running from the surface to depth of 2766 metres, with the 57 three component analogue geophones clamped at 15 m intervals at a depth of 1900 m (see Miller et al, and Harris et al) [5,7]. Dynamite charges (670 -1 kg charges at a depth of 15 metres in a 72 by 144 m grid) were the source of the seismic waves. Figure 6 shows the raw data from the DAS versus geophones, from a 470 m offset shot.

As summarized in Roach et al., the February 2016 results indicated:

- Excellent repeatability of results with earlier surveys, and the newly acquired data achieved a global NRMS of 10%, which allowed for the detection of the small amounts of CO$_2$ in the reservoir at significant depths.
- CO$_2$ plume was confirmed in the Upper Deadwood Formation at ~3260 m, extending a maximum of 200 m away from the injection well
- CO$_2$ levels in the Back Island and Lower Deadwood are below the seismic detection thresholds as of February, 2016.
3.2. Additional Seismic Work – ACROSS and Passive Seismic Monitoring

Aquistore’s field testing laboratory contains additional seismic monitoring technologies. In collaboration with JOGMEC (the Japan Oil, Gas and Metals National Corporation) the project installed a stationary, permanent seismic source at the site. This technology, called the “accurately controlled routinely operating signal system” or ACROSS established a permanent seismic source fixed in concrete that provides a stable seismic wave, always from the same location, thus providing excellent repeatability of testing conditions. While conventional seismic sources were used at Aquistore (vibroseis and dynamite) during testing at the site, ACROSS is providing a seismic source to potentially conduct real time monitoring of the subsurface utilizing the permanent array geophones.

Aquistore has also been conducting continuous passive seismic testing at the site –through the use of the permanent seismic array, a downhole array and also with three additional broadband stations to the northeast, northwest and southwest of the injection and observation wells. The passive seismic monitoring has determined, as of March 2016 that no injection-induced seismic activity has been detected.

3.3. Reservoir Fluid Sampling

Aquistore’s Fluid Recovery System (FRS) is a downhole device in the observation well that is specially designed to allow reservoir fluids to be sampled and brought to the surface under "in-situ" conditions. The FRS incorporates a system of shuttle valves where the FRS port is pushed into the borehole wall at the sampling interval in order to enhance hydraulic communication with the reservoir. By characterizing fluid compositions before and after CO₂ injection, this fluid recovery system has become a valuable tool for collecting hydrogeological information from within the storage container and has provided information on CO₂ and reservoir brine interactions.

Downhole fluid sampling has been conducted in various other pilot studies injecting CO₂ into the subsurface. The Cranfield [8] Project and the Otway Project in Australia [9] have both featured continuous collection of reservoir fluid samples near in-situ conditions, but Aquistore demanded a system that could be deployed in a casing-conveyed system to ensure the observation well casing remained open for time lapse logging. The FRS is illustrated in Figure 7.

Figure 7. Aquistore’s fluid recovery system

In February 2015, four baseline flushing operations were conducted in the FRS prior to CO₂ injection (injection began in April of 2015). In May and July 2015 two sampling operations of fluids from the injection zone depths were completed. Potential CO₂ breakthrough was observed at the observation well in July 2015. Figure 8 illustrates the effect of the arrival of CO₂ from readings taken in May (left) and July (right).
The observed electrical conductivity and temperature of water recovered from the FRS on May 29th 2015 (left) is plotted as a function of the volume of water injected during flushing of the FRS lines. The system behavior during the flushing of July 25th 2015, illustrating the effect of CO₂ on conductivity and temperature is clear (right).

Additional sampling from the observation well of fluids and gases from the target formation were collected in September and December 2015, and again in March 2016.

3.4. Surface and Near Surface MMV

3.4.1. Tiltmeters, Global Positioning Systems (GPS) and InSAR Reflectors

A number of technologies are being tested at the Aquistore site to determine if there is any surface uplift due to CO₂ injection. Such minute measurements are possible using various kinds of equipment, and prior to injection it is important to provide baseline measures to observe natural trends of surface deformation over time (allowing for seasonal influences, weather events, etc.). Aquistore is deploying three different monitoring technologies – tiltmeters, GPS and InSAR.

In order to create an effective and efficient tiltmeter array at Aquistore, a design was adopted that covers the goals of the surveillance program and matches the reservoir models created. The initial reservoir simulation indicated that the CO₂ plume would reach a diameter of less than 1 km in one year would grow up to 3 km in the long term. To cover this specification, 6 tiltmeters have been installed as indicated by the green dots in Figure 9. With spacing between tiltmeters sites of less than 1 km, this tiltmeter array can bring adequate coverage and resolution for mapping and potential injection induced deformation.
A big factor in tiltmeter array performance is the depth of installation. Previously the same tiltmeters were installed at 6m depth, where large spikes due to surface noise, temperatures and surface metrological condition were observed. To reduce the impact from surface, the tiltmeters have been installed deeper. Another factor taken into consideration is that the monitoring site at Aquistore is one that was reclaimed from coal open pit mining, where surface materials may be disturbed soil to depths of about 10 metres. In order to avoid the uncertainty of measurements, the final chosen depth of tiltmeters was 30 m below ground surface. This depth has helped avoid the effect of cultural noise (roads, vehicles, etc.) and the impact of temperatures at the surface.

Additional external influences for tiltmeter readings include barometric pressure and earth tide signals, and the effects of these cannot be reduced through increasing depth. It is possible to reduce these impacts through statistical regression methods as it moves beyond baseline measurements and monitors potential surface deformation.

Global Positioning Systems and InSAR (interferometric synthetic aperture radar) technologies are also included at the same super stations as the tiltmeters. InSAR creates digital images of surface deformation by sending phase waves to a satellite and comparing waves over different intervals to ascertain if any uplift or other movements of the surface have occurred. GPS, similarly, sends signals to positioned satellites over a time period to see if surface movements have occurred. These technologies have been collecting measurements at the Aquistore site since 2012, and as of early 2016 had not recorded any surface changes attributable to injection (for detailed baseline findings at Aquistore using these two technologies see Samsonov et al. [10]). An InSAR vertical motion map, indicating deformation from June 2012 to November 2013 (prior to CO₂ injection) is provided in Figure 10.
3.4.2. Soil Gas and Groundwater Monitoring

Groundwater and soil gas monitoring have been an integral part of Aquistore’s research program. Groundwater at Aquistore is measured from a number of monitoring wells – including those that were drilled as part of the research program to various depths around the project site (from 4 to 42 m depth), along with additional nearby domestic and pre-existing SaskPower owned wells. Figure 11 provides the location of water sampling throughout the project area and locations nearby.

Aquistore completed water sampling runs on five occasions prior to the injection of CO₂ between December 2012 and August 2014, and an additional sampling in October 2015 after injection began.

The five pre-injection surveys of groundwater chemistry found that results were highly variable across the region. High sodium and sulphate readings were observed in some wells and were likely caused by dissolution of gypsum and cation exchange between calcium in solution and sodium on clay materials. These baseline readings were indicative of the strip mining that had occurred in the area decades before, and likely led to high total dissolved solids (TDS) in the wells studied. Sampling after injection began revealed that for all significant chemical tracers, results were relatively consistent and unchanged. Only a handful of single-ion changes were detected – likely owing to well-construction related activities at the wells and not related to CO₂ injection.

Soil gas sampling at the Aquistore site and in several locations adjacent to it, is undertaken on a semi-annual schedule. That sampling relies heavily on geochemistry and, specifically, certain tracers with concentrations that don’t vary except during seepage situations. Soil gases have been sampled at 49 locations in a 7 km by 7 km grid around the site for the compounds indicated in Table 1. The table also indicates the methods of sample extraction, with the top four groups of elements being sampled from 1 m depth, and the surface flux of CO₂ being measured in the atmosphere by a portable device (Licor LI-8100).
Table 1. Elements analyzed in soil gas sampling at Aquistore site.

Soil gas sampling occurred three times prior to injection (November 2012, September 2013 and November 2014) and has happened three times since injection began (July 2015, January 2016, and August 2016). The November 2014 through January 2016 sampling periods have included jointly the soil gas well sampling and flux sampling. Results pre-injection indicate the soils in the sampling grid are hard, light and compact, with significant accumulations of naturally produced CO2 in places where soil wetness (ground low points, or particularly rainy seasons) enhanced CO2 storage by limiting outward diffusion.

Comparisons of pre- and post-injection measurements indicate that there are no signs of seepage of CO2 at the site. Particular tracers are more useful for making this determination than others. Radocarbon-CO2 (or 14CO2) is not present in the injected CO2 at Aquistore because the source of the CO2 is from coal, whereas natural organic decay in surface soils are expected to have abundant levels of 14CO2 because the organic matter under decay at surface is expected to be young. This contrast in isotopic signatures can provide for a strong tracer signal of CO2 seepage. While the sampling program has not found any changes in 14CO2 since injection, it has identified depressed 14CO2 in the reclaimed former surface coal mine area, which is attributable to microbial attack of the coals, and gaseous decay products like CO2 which retain in the 14C-deplete signature of the fossil organics from which they were produced. As a result, the monitoring program is prioritizing use of 14CO2 only in parts of the site where it is a powerful tracer, and relying on other indices for use in the reclaimed mining area. Analyses are ongoing, with the project also determining baselines for various compounds and using new ratio-based methods such as respiratory exchange ratio (RER – as highlighted in the work of Romanak et al.) [11] which uses ratios between O2 and CO2 in the soil to help pinpoint natural/unnatural levels of CO2, taking into account seasonal variations and other differences.

4. Conclusions

The Aquistore Project’s main goal is to demonstrate that CO2 injection from a coal-fired power source into a deep saline geological formation is a safe and workable solution for reducing GHG emissions from such set point sources. The project is, therefore, informing not just participating industry sponsors and researchers in different countries about results, it is also working with regulators – provincial, federal (Government of Canada) and international (USDOE, others) – to evaluate and identify appropriate measurement, monitoring and verification methods that would allow for the creation of more storage projects going forward. Although Aquistore is still in its first year of CO2 injection, it has already provided data on the effectiveness of several technologies and has cross-compared several monitoring and measurement methods. The results have so far demonstrated that imaging a CO2 plume at depths not identified before (3.3 km), is possible. The comparison between standard geophone receivers and DAS will demonstrate the capabilities of both these technologies. DAS results from the project have drawn interest from beyond the CCS industry, from mining and oil companies.

Early results from Aquistore in the areas of reservoir fluid monitoring (chemical interactions in the reservoir being observed as CO2 injection increases) along with groundwater and soil gas monitoring are helping to shape recommendations for future projects. Many methods being deployed to measure and monitor at the injection site
will help reduce costs and risks for other projects going forward through recommendations on appropriate technologies to be deployed.

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