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Aquistore Project Measurement, Monitoring, and Verification: From Concept to CO_2 Injection

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Abstract

As an independent research and monitoring project, Aquistore intends to demonstrate that storing liquid carbon dioxide (CO_2) deep underground (in a brine and sandstone water formation), is a safe, workable solution to reduce greenhouse gases (GHGs). Managed by the Petroleum Technology Research Centre, Aquistore is built upon the learnings of the IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project, where over 22MT of CO_2 have been stored in an oil field during EOR operations. As a global leader, PTRC has over a decade of experience in CO_2 storage and monitoring work.

Aquistore is Canada's first dedicated CO_2 storage project, and is an integral component of SaskPower's Boundary Dam Integrated Carbon Capture and Storage (CCS) Demonstration project - the world's first fully integrated CCS demonstration project from a coal-fired power plant. As an unique CCS project, Aquistore is providing buffer storage to this commercial CO_2 capture plant and active oilfield EOR operations. In collaboration with SaskPower, Aquistore will be the first integrated project globally to demonstrate deep saline CO_2 capture, transport, and storage on a commercial scale from a coal fired power plant. CO_2 will be captured at unit 3 of the Boundary Dam power-station (BD3), transported via underground pipeline to the Aquistore site, and injected to a depth of 3.4 km.

The Winnipeg and Deadwood formations, which constitute the deepest units within the Williston Basin and were chosen as the target zone for CO_2 injection. These geological formations have much greater capacity for storing CO_2 than any oil reservoir in western Canada. The suitability of the storage complex was investigated through 3D

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characterization using high-resolution 3D seismic images and data from the injection and observation wells. These data show that: there are no significant faults in the immediate area of the storage site; the regional sealing formation is continuous in the area; and lastly, that the reservoir is not adversely affected by knolls on the surface of the underlying Precambrian basement.

In the Aquistore project PTRC has brought together internationally recognized expertise and diverse interests. Research in monitoring methods is central to the Aquistore Project. A permanent areal seismic monitoring array has been deployed which comprises 650 geophones installed at 20 m depth on a 2.5x2.5 km regular grid. The objective of this array is to test "sparse array" seismic imaging and to provide continuous passive monitoring. This array is being utilized in conjunction and comparison with time-lapse 3D seismic imaging, continuous microseismic monitoring, vertical seismic profiling, cross-well seismic tomography, and broadband seismographs.

Injection-related surface deformation monitoring is provided by InSAR analysis in conjunction with a network of tiltmeters and GPS stations. Electromagnetic surveys and gravimeters are also being used. In an effort to minimize surface impact these monitoring technologies - where possible - have been collocated and solar-powered.

Surface electromagnetic methods and time-lapse gravity monitoring will be tested in conjunction with deployment of a fibre-optic distributed acoustic sensing (DAS) line. A fibre-optic distributed temperature sensing (DTS) line is also installed. A unique fluid recovery system (FRS) as well as casing conveyed pressure and temperature gauges will contribute to the project's down-hole monitoring techniques.

Aquistore's MMV program will test and develop effective methods for monitoring CO_2 storage sites and ensure conformance of the storage process through continuous monitoring. This program is seeking to minimize the risk associated with any potential leakage of CO_2 from the storage reservoir through early detection. Aquistore's MMV program has included an added focus on integrated monitoring methods such as the inclusion of non-seismic methods and constraints from reservoir flow simulations. Aquistore will provide an efficient, cost effective, and field-tested basis for designing effective MMV programs for other similar projects worldwide.

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Keywords: CCS; deep saline storage; MMV; baselines; Canada; active projects; CO2 storage; Saskachewan.

1. Introduction

Aquistore is providing a storage option to the Boundary Dam Carbon Capture and Storage Demonstration Project – the world's first commercial scale, post-combustion CCS project associated with a coal-fired electrical generating station. Begun as an independent project in 2009, Aquistore joined forces in a unique partnership with SaskPower, a provincial Crown corporation, to demonstrate that deep saline sequestration is a safe, feasible solution to reducing greenhouse gas emissions. The Aquistore site, located 2.8 km from SaskPower's Boundary Dam Power Station, will receive CO_2 via pipeline, from SaskPower.

A majority of the CO_2 captured at Boundary Dam will be sold to Cenovus Energy for enhanced oil recovery (EOR) in oil fields located outside of Weyburn, Saskatchewan. While this EOR offtaker is secure and a source of potential revenue for SaskPower, Aquistore provides not only a research component, but a secure storage alternative. By offering buffer protection, Aquistore may allow its supplier and the EOR offtaker to mitigate any delays or interruptions encountered without having to vent CO_2 into the atmosphere.

With the two deepest wells in the province of Saskatchewan, Aquistore will be injecting 3.4 km deep into the Winnipeg and Deadwood formations. With a suite of proven and pilot monitoring techniques, Aquistore will demonstrate best practices in CO_2 monitoring with attention to both economics and efficiencies. Managed by the

Petroleum Technology Research Centre, Aquistore is continuing to build on the 10+ years of management and experience gained during the *IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project*.

As Canada's first targeted deep saline CO_2 storage project, Aquistore is providing Canada and the world with valuable insight and lessons learned in commercial CO_2 storage. Aquistore was built on the learnings of the *IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project* and has been overseen by PTRC from the plenary stages to its current commercial state. One of only a handful of active projects internationally, Aquistore has brought together the interests of research and industry. This paper will provide a summary overview of Aquistore from start to finish, from site characterization to surface preparations and downhole monitoring. Once CO_2 injection commences, Aquistore will serve as an industrial scale research site for cutting-edge CO_2 measurement, monitoring, and verification technologies.

2. Project Management and General Overview

The Petroleum Technology Research Centre provides overall management of the project. PTRC is responsible for the funding, administration, and managerial aspects of the project. While SaskPower owns the Aquistore assets (an injection and observation well) as well as the long term liability, PTRC will be managing the research and monitoring program associated with the SaskPower Boundary Dam Integrated CCS Demonstration Project.

Scientific oversight, guidance and research direction is provided by at Science and Engineering Research Committee (SERC). With combined decades of research and first-hand experience on CCS projects, the members of the SERC committee were selected to contribute to a research program focused on: geological and hydrogeological characterization; reservoir modeling and simulation; wellbore design; well instrumentation; geomechanical analyses; geochemical monitoring; reactive transport modeling; seismic and remote monitoring methods; and risk assessment and risk management

3. Site Characterization and Geology

Aquistore is the only CO_2 storage demonstration project, proposed for the Williston Basin.

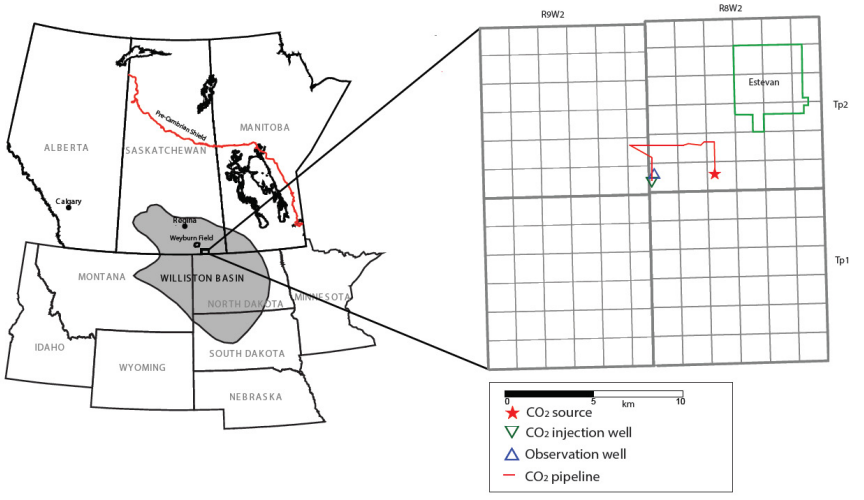

Fig. 1: Location Map showing the Williston Basin and the enlarged area with the CO_2 source and Aquistore's injection and observation wells.

Prior to drilling, significant work programs were undertaken to characterize the geological and hydrogeological nature of the selected site to ensure suitability. Examples of these specific programs include: establishment of the

hydro-stratigraphic framework; examination of well-files (DTS, RFT, pressure data, etc); isopachs of geological units; core studies; characterization of porosity/permeability; compilation of existing subsurface fluid flow data; and preliminary fluid flow simulations. In addition, significant modelling work was undertaken.

The global depth criterion for storage is considered to be within the range of 1000-3500m. Aquistore's target injection zone is a saline aquifer, comprised of sandstones of the Winnipeg and Deadwood formations, which occur at depths over 3200m at the project site. The Winnipeg and Deadwood formations are the deepest units within the sedimentary sequence. These sandstones are overlain by a thick and laterally extensive shale horizon (the Icebox Member of the Winnipeg Formation). The Deadwood Formation is a regionally extensive sandstone of variable grain-size that contains intervals of silty-to-shaley interbeds. The overlying Winnipeg Formation comprises a lower sandstone called the Black Island Member and an upper shale, the Icebox Member which serves as the primary seal to vertical migration.

Located in south-eastern Saskatchewan near the city of Estevan, Aquistore is home to the two deepest wells in the province. Drilled in 2012, these two wells became the key data points for the area. At a depth of 3396 m and 3400 respectively, the injection well, observation well, and three cores, have helped characterize geology not only for the project but for the region. Of the core retrieved, 20 m were collected from the lowermost section of the Basal Cambrian saline system (Deadwood formation). An additional 28 m of core from the Winnipeg Icebox Shale/ Black Island Sand formations were collected which include samples of caprock and the transition to the top of the reservoir for a total length 48 m of core. To complement these cores, 30 side-wall cores were taken using a rotary side wall core during drilling.

4. Measurement, Monitoring, and Verification.

Aquistore's MMV program is built upon the premise of testing and developing effective methods for monitoring CO_2 storage sites and ensuring the conformance of the storage process through continuous monitoring. Both the surface and deep subsurface monitoring technologies were selected to minimize the risk associated with potential leakage of CO_2 from the storage reservoir through early detection. In addition to these 'traditional' concerns, Aquistore's MMV program has an added focus on integrated monitoring methods as no one technique in isolation can provide the information that is required of MMV protocols. In principal, if used together and in combination with fluid flow simulations and geomechanical modeling, they could be capable of providing an improved quantitative estimate of subsurface CO_2 distribution. Through the field-testing of a number of pilot technologies, Aquistore will provide a field-tested basis for designing effective MMV programs for other CCS projects world-wide.

4.1. Surface-based Measurement, Monitoring, and Verification

Aquistore has a suite of monitoring technologies installed on the surface, shallow subsurface, and deep subsurface. In addition, there are a number of seismic monitoring technologies which are considered separately from the 'general' MMV program. The surface based monitoring technologies include:

Groundwater Sampling

Groundwater monitoring is an integral part of any CCS MMV program. As an essential part of Aquistore's assurance monitoring program, three baseline surveys of 40 groundwater wells have been sampled in this program, including several domestic wells and pre-existing SaskPower owned wells. Twenty dedicated wells were drilled to various depths between depths of 4-42 m in advance of CO_2 injection. These samples, and those from the groundwater wells, have been analyzed for major, minor, and trace elements as well as oxygen and stable carbon isotopes [1].

Soil-gas Monitoring

Along with groundwater monitoring, soil gas monitoring can be a subject of great public concern and subsequent scrutiny. As a result, Aquistore has undertaken a number of different monitoring methodologies including: specific soil gas concentrations; continuous soil gas measurements; isotopic signatures (stable and radiogenic carbon); surface CO_2 flux.

50 semi-permanent surface probes were installed at a depth of one to two metres at 46 different locations. During each sampling, every probe port was sampled for 20 – 30 minutes of flux recording time. These probes were sampled for the following compounds He, H_2, CO_2, O_2, N_2, H_2S, C1-G7 and hydrocarbons concentrations. In addition, an analysis of the stable isotope $\delta^{13}C$ and radiogenic isotope ^{14}C was completed.

A survey of 100 sites at a depth of 1 m was conducted with soil gas analysis for CH_4, CO_2, $\delta^{13}CH_4$, N2, and Ar, with soil surface efflux conducted simultaneously for CO_2 and CH_4.

Atmospheric Monitoring

In addition to the flux sampling detailed above, a secondary atmospheric monitoring and sampling program was undertaken. This multispecies drive-around survey samples CH_4, CO_2, H_2S, and $\delta^{13}CH_4$ every 10-20 meters of accessible road on site.

Tiltmeters

Aquistore has an array of six tiltmeters which have been deployed in 30 metre boreholes. This technology will measure surface deformation associated with CO_2 injection and storage. The tiltmeter array is equipped with communication units to provide remote data access and a weather station to provide surface conditions for the system. Baseline data have been successfully recorded and downloaded remotely since November 2012.

InSAR and Global Positioning System (GPS)

In conjunction with tiltmeter data, remote sensing techniques such as InSAR and GPS have the potential to determine changes in subsurface fluid distribution, pressure changes and associated surface deformation. Over a 6.5 km^2 area Aquistore has deployed 9 InSar reflectors and 8 dedicated GPS stations with baseline data collected since November 2012.

Borehole to Surface Electromagnetic (BSEM) Survey

In association with Carbon Capture Project 3 (CCP3), a baseline electromagnetic survey was undertaken by transmitting an electric current to reservoir depth and recorded through a surface array of electric field sensors oriented radial to the well. This new electromagnetic source configuration has the potential to extend electromagnetic methods to reservoir monitoring in deep formations such as at Aquistore.

Time-lapse Gravity

Aquistore is incorporating surface time-lapse gravity measurements for monitoring CO_2 in the subsurface by making repeated gravity measurements along two orthogonal profiles. Surface gravity measurements have been made twice per year to determine the maximum background seasonal variations seasonal gravity variations.

5. Downhole Measurement, Monitoring, and Verification

5.1 Seismic Program

Aquistore has an extensive seismic program built on the learnings of the *IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project*. The seismic program is composed of traditional 2D and 3D seismic, a unique permanent areal array and distributed acoustic sensing (DAS) fibre optic line for seismic surveys. Traditionally, 3D seismic is a primary technology for CO_2 monitoring. Aquistore acquired 2D and several 3D seismic data sets and results in the initial baseline phase of the project. Once CO_2 injection has begun in earnest, repeat surveys will be shot to provide difference data.

Aquistore's permanent array aims to demonstrate a significantly more-cost-effective seismic acquisition method. In March 2012, Aquistore installed a permanent seismic array composed of 630 geophones installed at a depth of 30 m. This installation will be used in conjunction and comparison with traditional 3D seismic.

The characterization of the reservoir and the survey acquired via permanent array will be used over the course of the project's monitoring program. In addition, the resulting data will be integrated with other surveillance data to fully inform the project's MMV program. Comparisons of data can be used to model time-lapse imaging of CO_2 movement, allowing the project to track and trace injected CO_2 as it moves laterally in the reservoir. Initial results from these surveys are encouraging as they show an improvement in repeatability by a factor of at least two relative to comparable results from the *IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project*.

In addition to the increased repeatability for time-lapse imagine, this array allows for continuous passive microseismic monitoring. 50 geophones traversing the array are kept constantly active monitoring local seismicity that is occurring as a baseline and/or may be induced by CO_2 injection.

5.2 Digital Acoustic Sensing Line and Digital Temperature Sensing Line

Aquistore's two wells are equipped with Distributed Temperature Sensing (DTS) lines. The injection well has DTS lines installed on the tubing string and the casing. The DTS line on the tubing string is designed to capture phase dynamic behaviour of the injected fluids over the course of the project. The data emerging from the casing conveyed DTS line and tubing DTS line will provide insight and observations related to well integrity. The observation well also features a DTS line which will assist in monitoring the arrival of the CO_2 plume at the observation well.

In addition, the injection well and observation well are equipped with Distributed Acoustic Sensing (DAS) lines. These permanently installed fibre optic cables eliminate the need for intervention and allows for repeatable seismic acquisition on demand. In addition to increased data acquisition, this DAS line is capable of being used at over 300^{o} Celsius and at over 10,000 PSI and has potential applicability for steam injection scenarios.

Two surveys of the permanent array have been shot. The most recent survey, occurring in March 2013, included two sources - vibroseis and dynamite - and 3 receivers – 3D lines, the permanent array, and a DAS line. This unique survey, believed to be the first of its kind, will allow for direct comparison of seismic techniques and has cross-industry relevance and potential. The DAS line has the potential to replace conventional geophones. Due to the inhospitable geological environment of many deep saline storage sites, the success of a DAS line has extraordinary potential in CCS as well as in commercial applications.

5.3 Fluid Recovery System

Aquistore's observation well is equipped with a unique, patent-pending Fluid Recovery System (FRS). The FRS is a downhole device specially designed to allow reservoir fluids to be sampled and brought to the surface under "in-situ" conditions from the fully cemented observation well. The FRS incorporates a system of shuttle valves which 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 CO_2 injection, this fluid recovery system will contribute to the understanding of hydrogeological behavior within the storage container. Information on the interaction of CO_2 and reservoir brine will also be examined.

Conclusion

Dedicated CO_2 storage projects are now gaining global recognition as necessary elements of our energy future. In anticipation of future CO_2 emission regulations, CO_2 storage may be the only option available for CCS operators to offset emissions or costs. Utilizing an unique suite of technologies and expertise Aquistore's CO_2 monitoring, measurement and verification program is moving towards the goal of quantifying stored CO_2. With an ideal project site, pioneering MMV program, and positive support from the local, provincial and federal government, Aquistore is helping to build capacity for CCS both in Canada and around the world. As Aquistore awaits CO_2 injection from partner SaskPower, Saskatchewan and the world are waiting. With a strong, established suite of baseline results, Aquistore will serve as a rigorous trial and demonstration for effective surface and down-hole technologies, and provide jurisdictions with evidence that CCS is a safe and accepted way to reduce greenhouse gas emissions.

Currently there are only a handful of large-scale commercial CCS demonstration projects active internationally. As the 'first-wave' of demonstration projects, each has had their own unique experiences both good and bad. As one of the few active CCS projects, Aquistore has invaluable experiences and lessons learned to share as the project prepares for CO_2 injection.

(1)

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