Development of conceptual design for commercial-scale geologic storage and monitoring system at American Electric Power Mountaineer Plant

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Abstract

A system design for injecting 1.5 million tonnes CO\textsubscript{2} per year at the American Electric Power’s Mountaineer Plant was developed using geologic and reservoir data from a smaller scale injection validation test and a new test well. The preliminary assessment shows that the thin vuggy zones in the Copper Ridge Dolomite layer have significant injectivity and are likely to fulfill the project needs with two injection wells and an accompanying monitoring system. The monitoring program included wells in the injection, intermediate, and shallow zones for pressure and fluid monitoring, wireline logging, micro-seismic monitoring, surface emissions, corrosion, and mechanical integrity. Cost estimates for the program indicates that the storage system cost is about 20\% of the total project cost, i.e., capture, transport, and storage; however, the cost uncertainty in storage is greater due to regulatory and geologic uncertainty.

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1. Introduction

In late 2009, Department of Energy (DOE) selected the American Electric Power (AEP) Mountaineer Plant in West Virginia, USA (Fig. 1) for demonstration of a commercial-scale Carbon Capture and

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Storage (CCS) system for capture and geologic storage of approximately 1.5 million tonnes of CO₂ per year. The overall objective of the project, named CCS II project, was to design, build and operate a commercial-scale CCS system capable of treating a nominal 235 Megawatt (MWe) slip stream of flue gas using Alstom’s chilled ammonia process. The project was planned for execution in four phases:

- Phase I – Project Definition (2010 – 2011),
- Phase II – Design & Permitting (2011 – 2012),
- Phase III – Construction & Start-up (2013 – 2015), and
- Phase IV – Operations (2015 – 2019).

Battelle was selected as the lead geologic storage contractor by AEP for Phase I. Phase I work included assessment of regional and local geology using seismic data; drilling, logging, coring, and testing of a validation well; reservoir modeling; system design; and cost assessment. We present the key findings related to Project Definition Phase for the geologic storage component, including results of site characterization, injection and monitoring system design, and cost uncertainties. More detailed information on the overall effort is provided in the Preliminary Public Design report on Phase I, prepared by AEP for the DOE [1].

1.1 Past and concurrent work at the site

The Mountaineer site is located in the Appalachian Basin, with approximately 3 km of sedimentary layers dipping gently (~1-2 degrees) to the southeast and overlying Precambrian igneous rocks. The CCS II geologic storage effort builds on the two previous projects at the site. This included the DOE funded
site characterization project conducted by Battelle from 2003 to 2007 and the Product Validation Facility (PVF) project funded by AEP. The PVF project included installation and operation of a 20 MWe CO₂ capture system using the Alstom’s chilled ammonia process and injection and monitoring of CO₂ in two deep saline formations at the site. The DOE funded project included seismic surveys and drilling of a wildcat well (AEP-1), which identified Rose Run Sandstone and the Copper Ridge Dolomite as potential injection zones [2, 3]. The PVF system was constructed from 2007 to 2009 and operated until mid-2011 with approximately 37,000 tonnes of CO₂ injection and currently is in the post-injection monitoring phase as of October 2012. The PVF system includes two injection wells (AEP-1 in Copper Ridge Dolomite and AEP-2 in Rose Run Sandstone) and three injection zone monitoring wells (MW-1, MW-2, MW-3) at locations shown on Fig. 2. The two injection zones used are: 1. Rose Run at about 2350 meter depth consisting of thin interlayered sandstone and dolomite zones and 2. Copper Ridge, a 200 meter thick dolomite layer with thin vuggy high porosity and permeability intervals in the lower portions at about 2500 meters depth. The PVF operational data showed that the Rose Run Sandstone injectivity is likely to be limited due to low permeability and relatively low fracture pressure. In comparison, the vuggy zones within the Copper Ridge [4] indicated high permeability, low pressure build-up due to injection, and no indication of a constraining boundary condition near the injection well. The characterization and monitoring data collected during the PVF project indicated that the vuggy zones in the Copper Ridge injection interval have significantly greater injectivity than the Rose Run Sandstone.

2. Geologic characterization

The CO₂ storage effort under the CCS II was designed to reduce key geologic uncertainties; develop a detailed roadmap for permitting, design, construction, operation, and monitoring of a reliable system; and develop initial cost estimates for further refinement under detailed design phase. Due to the lack of sufficient number of deep wells in the area there is limited understanding of the continuity of target zones away from the PVF area wells which are located in close proximity to each other. In vuggy dolomites verifying this continuity is especially crucial for developing successful projects. However, geologic continuity and regional development of the porosity zones for a commercial-scale system was unknown and therefore, additional characterization was deemed necessary in a 2705 m deep test well (BA-02 well) located about 3 km from the PVF wells. The well was designed (Fig. 3) for potential future use as a monitoring well. In addition, about 40 km of 2-dimensional seismic lines were purchased and interpreted to verify that there are no geologic structures of significance within the limit of resolution of the seismic data.
The geologic column for the BA-02 (Fig. 4) indicates that the overall geology in this area is similar to the PVF area, consisting primarily of thick shale and carbonate rock sequences. The well characterization included a full suite of wireline logs in the lower portion consisting of basic gamma ray, neutron, density, resistivity, dipole sonic, elemental spectroscopy, and nuclear magnetic resonance to help assess the full...
range of rock properties. In addition, 9 m of full core was collected in the Black River limestone (Fig. 4a), one of the several containment zones, and 82 m of core was collected in the Copper Ridge Dolomite in an effort to sample the vuggy dolomite intervals (Fig. 4b and 4c). This supplemented previous cores taken from the Rose Run Sandstone in AEP-1 well. Overall, the logs and cores indicate potential of injection in the Rose Run and Copper Ridge along with possible additional zones in the Beekmantown Dolomite, overlying the Rose Run. However, the porosity and permeability in Copper Ridge vuggy zones is significantly greater than in the other zones, which is indicated by the presence of very large vugs seen visually (Fig. 4b) and in CT scans (Fig. 4c) of the core samples. These vuggy zones are also seen in the image logs from BA-02 (Fig. 5) and AEP-1 wells. Overall, the log and visual evidence of permeability zones is supported by the core analysis results.

Fig. 4. Core samples showing examples of (a) Black River containment zone; (b) vuggy dolomite in lower Copper Ridge; and (c) CT-scan of the lower Copper Ridge vuggy zones.
Fig. 5. Image log across the lower Copper Ridge Dolomite, showing presence of vuggy porosity.

The hydraulic characteristics of candidate injection zones were assessed by conducting flowmeter logging surveys at static and dynamic conditions, drill-stem tests, and brief injection tests within these zones. Borehole flowmeter surveys have been found to be useful and a low-cost screening technique for identifying possible injection zones for more detailed testing. In BA-02, dynamic flowmeter surveys were conducted at three different flow rates (Fig. 6). The figure shows that a vast majority of the flow is going into the lower Copper Ridge section corresponding to the depth of the vuggy zones with minor inflow in the Beekmantown and Rose Run zones. Results of drill stem and injection tests confirmed presence of injectivity in all of these zones and quantified key hydrogeologic parameters of each zone (Fig. 7). The reservoir testing results in BA-02 are consistent with the observed pressure response in PVF wells, which showed Copper Ridge well (AEP-1) as having at least 100 times more injectivity than in the Rose Run Sandstone.

3. Reservoir modeling

The design assessment for the injection system was conducted using CO₂ sequestration version of the STOMP code and the model configuration is shown in Fig. 8. Geologic data from the PVF wells and initial drilling information from the BA-02 wells was used in developing the model. A number of well
layouts and injection schemes were analyzed for preliminary optimization of a number of wells, the CO₂ plume area, and pressure build-up. The selection of well sites also accounted for pipeline routing, property ownership, environmental issues, and proximity to the source. The reservoir simulations indicated that two injection wells located at AEP properties about 3 and 17 km away and completed in the lower Copper Ridge zone alone could satisfy the storage requirements of 1.5 million tons of CO₂/year for a period of 5 years (selected simulation time) as shown in Fig. 9. Simulated pressure profiles over time at three distances (Fig 10) from the injection wells were also used for preliminary siting of monitoring wells. Although injection in other zones, such as the Rose Run and Beekmantown, could be conducted, doing so could add to the construction and monitoring costs without significant reduction in CO₂ plume size or pressure zone.

Fig. 6. Composite plot showing results of BA-02 well flowmeter data for 2, 4 and 6 barrels/minute dynamic surveys.
Fig. 7. BA-02 well results for permeability-thickness profiles in the borehole.
Fig. 8. Reservoir model configuration showing candidate injection zones

Fig. 9. Reservoir simulation results for Copper Ridge after 5 years at 1.5 MMT/year (a) Cross section of pressure; (b) CO₂ footprint
4. Storage system design

The conceptual storage system design was developed based on the results of site characterization, experience gained from the PVF project, site access, and pipeline routing. Although several potential injection configurations are possible, based on site data and modelling, it appears that one injection well each located in the Borrow area and the Jordan Tract properties and completed in the Copper Ridge Dolomite will be sufficient. However, this would be need to be further validated through an additional test well, regional geologic work, and possibly 3D seismic surveys. A layout of the injection locations, simulated plume size, and likely monitoring well locations is shown in Fig. 11. Preliminary designs for the injection and monitoring wells were developed as part of the Phase I work.

A monitoring plan to address the requirements of the Class VI Geologic Storage wells under the Underground Injection Control (UIC) by U.S. Environmental Protection Agency was developed. This plan includes wells for pressure and fluid monitoring in deep wells in the reservoir, in intermediate zones, and in shallow groundwater wells. Other monitoring methods include periodic pressure fall-off, microseismic monitoring, surface emissions, corrosion and mechanical integrity testing, and periodic wireline logging as summarized in Table 1 and detailed in the preliminary monitoring plan [1]. At this time, no form of repeat seismic was anticipated for CO2 plume tracking for the commercial-scale project. Based upon results of the cross-well seismic survey at the pilot-scale project, the depth of the Copper Ridge and the thin injection intervals, it does not appear that seismic monitoring is a suitable CO2 plume tracking technology for this site.
Fig. 11. Layout of CO$_2$ injection and monitoring system. Yellow circles represent estimated CO$_2$ plumes in the Copper Ridge.
Table 1. Preliminary monitoring schedule for the five-year CO2 storage project.

| Monitoring and Testing Methods                                      | Baseline                                                                 | Active Injection Phase               |
|-------------------------------------------------------------------|--------------------------------------------------------------------------|--------------------------------------|
|                                                                   | Pre-Injection                                                            | Year 1 to Year 5                      |
| Quarterly sampling and analysis of the CO2 injection fluid         | NA                                                                       | XXXX                                 |
| Monitoring of injection rate volume, pressure, and temperature; annulus pressure and annulus fluid volume | NA                                                                       | Continuous                           |
| Corrosion monitoring of well materials                            | NA                                                                       | XXXX                                 |
| External mechanical integrity testing (MIT)                       | X                                                                        | X                                    |
| Pressure Fall-Off Testing                                        | NA                                                                       | X                                    |
| USDW aquifer groundwater monitoring                               | >1 year (quarterly)                                                     | XXXX                                 |
| Groundwater quality and pressure monitoring in Intermediate Zone(s)| X                                                                        | X                                    |
| Microseismic Monitoring for Injection Induced Fracturing          | ≥1 month                                                                | Continuous                           |
| PNC Logging for CO2 Detection                                     | X                                                                        | X                                    |
| Injection Reservoir Fluid Chemistry Monitoring                   | X                                                                        | X                                    |
| Injection Reservoir Pressure Monitoring                           | ≥3 months                                                               | Continuous                           |
| Modeling                                                          | X                                                                        | X                                    |
| Surface emissions monitoring                                      | 1 to 2 years(a)                                                          | XXXX                                 |

X: represents single sampling/survey event (a) Quarterly or monthly frequency

The specific testing and monitoring requirements for the commercial-scale project are not known at this time because UIC permit has not yet been issued for the project. Therefore, it was assumed that testing and monitoring requirements for the commercial-scale project will be based on experience gained from the ongoing PVF pilot-scale CO2 capture and storage project at the Mountaineer Power Plant. It was also assumed that the testing and monitoring requirements in the new Geologic Sequestration (GS) Rule will apply. The pilot-scale project is authorized by West Virginia Department of Environmental Protection (WVDEP) UIC Permit No. 1189-08-53, a Class V experimental well permit. The Class V permit stipulates testing and monitoring requirements to verify that the experimental geologic sequestration project is operating as permitted and is not endangering underground sources of drinking water (USDW). The monitoring program also included consideration of the Mandatory Reporting of Greenhouse Gases Rule (MRR) (74 FR 56260), which requires that all facilities that inject CO2 for the purpose of long-term geologic sequestration report basic information on CO2 injected underground and imposes additional monitoring to quantify CO2 emissions to the atmosphere.

Assessment of in-situ stresses, acceptable pressure increase, and potential for induced seismicity is an important part of CO2 storage site selection. In the initial work at AEP-1 during 2003 to 2005, there was significantly more data available for the Rose Run Sandstone and this has been published [e.g. 2, 3] with regard of use of this candidate injection zone for demonstration purposes. However, it has been clear that this zone may have relatively low injectivity for commercial scale projects. Lucier et al [5] have evaluated geomechanics of the Rose Run and Zoback and Gorelick [6] have published concerns about
ability of Rose Run to accept the entire CO₂ output from the plant, with respect to pressure build up and potential for induced seismicity. However, the information about significantly higher injectivity and favourable stress profiles in the Copper Ridge vuggy zones has not been incorporated into the opinions expressed by Zoback opinion article [6]. Although, more work is needed to verify the local and regional geomechanical characteristics and geologic continuity, based on the PVF and CCS II project research, it appears that Copper Ridge will be a suitable candidate for injection at the scale proposed in CCS II project.

5. Cost Estimates

A key element of the Project Definition phase was to prepare a preliminary cost estimate (+/-25%) and schedule for future phases. The storage cost elements were combined with the capture, transport, and other costs by AEP to develop full system budgets for all four phases [1]. Total estimated cost was $1,065 million including overnight (capital) cost ($825 million), escalation ($71 million), risk based contingency ($103 million) and operations ($66 million), representing a 99.5% confidence level that the project could be completed at or below this estimate. The estimated overnight cost of the CO₂ storage component is $160 million or ~20% of the entire CCS II project. However, the uncertainty analysis on cost risks showed that the storage related elements, along with material price volatility and potential labor overtime costs, add significantly to cost uncertainty. This is largely due to uncertainty in regulatory requirements for the number of monitoring wells, possible need for a back-up injection well, and the possible need for 3D seismic over a large area in Phase II. Many of these cost risks would have been resolved through activities planned for Phase II, including discussions with regulatory authorities to clarify exact monitoring requirements and additional characterization to reduce geologic uncertainty.

6. Conclusions and Current Status

During July 2011, AEP decided to place the project on hold due to lack of climate regulations, price on carbon emissions, and lack of a feasible mechanism to recover the project costs. However the geologic, operational, monitoring, engineering, and cost experience gained at this site during the last 10 years continues to be a useful reference for other CCS projects and will form the basis for any future work at the site. Specifically, the investigations have led to identification and qualification of a preferred injection zone in the Copper Ridge Dolomite in the northern Appalachian Basin. These carbonate rocks require different exploration strategies than the regionally extensive sandstones such as the Mt. Simon Sandstone to the west of the site, but are likely to offer large-scale injection potential. The regional continuity, injectivity, and exploration options for these zones in the region are being investigated further under follow-on projects with DOE and state funding by Battelle.

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