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Using pulse testing for leakage detection in carbon storage reservoirs: A field demonstration

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ABSTRACT

Monitoring techniques capable of deep subsurface detection are desirable for early warning and leakage pathway identification in geologic carbon storage formations. This work demonstrates the feasibility of a pulse-testing-based leakage detection procedure, in which the storage reservoir is stimulated using periodic injection patterns and the acquired pressure perturbation signals are analyzed in the frequency domain to detect potential deviations in the reservoir's frequency domain responses. Unlike the traditional well testing and associated time domain analyses, pulse testing aims to minimize the interference of reservoir operations and other ambient noise by selecting appropriate pulsing frequencies such that reservoir responses to coded injection patterns can be uniquely determined in frequency domain. Field demonstration of this pulse-testing leakage detection technique was carried out at a CO_2 enhanced oil recovery site—the Cranfield site located in Mississippi, USA, which has long been used as a carbon storage research site. During the demonstration, two sets of pulsing experiments (baseline and leak tests) were performed using 90-min and 150-min pulsing periods to demonstrate feasibility of time-lapse leakage detection. For leak tests, an artificial leakage source was created through rate-controlled venting of CO_2 from one of the monitoring wells because of the lack of known leakage pathways at the site. Our results show that leakage events caused a significant deviation in the amplitude of the frequency response function, indicating that pulse testing may be deployed as a cost-effective active monitoring technique, with a great potential for site-wide automated monitoring.

1. Introduction

Carbon capture and storage (CCS) is being pursued as a large-scale mitigation option for making dramatic reductions in greenhouse gas emissions from power plants and other industrial sources. A recent report by the International Energy Agency points out that CCS is the "only technology available today that has the potential to protect the climate while preserving the value of fossil fuel reserves and existing infrastructure" (IEA, 2013). For geologic storage, supercritical CO_2 is injected into deep geologic formations that are typically located 1–3 km below surface (e.g., depleted oil and gas reservoirs, unminable coal seams, or saline aquifers). Potential leakage through abandoned wells and geologic faults represent the greatest risk to geologic carbon storage projects. To ensure containment efficiency and public safety, the fate and transport of injected CO_2 plume must be closely monitored during the life cycle of a geological sequestration project. Over the last decade, a wide array of monitoring methods have been developed and demonstrated for leakage detection, including pressure monitoring, soil gas monitoring, groundwater sampling, geophysical surveys, vegetation stress, eddy covariance, and remote sensing (Lewicki et al., 2007; Trautz et al., 2012). Leakage pathways tend to be more diffused and the leak signals more attenuated as the distance from the source increases. Thus, monitoring methods/instruments capable of deep subsurface detection are more desirable for early warning and leakage pathway identification. Common methods suitable for deep subsurface monitoring can be roughly classified into surface-based and downhole technologies. The former mainly includes time-lapse seismic surveys, while the latter includes wellbore sensors and tools such as downhole pressure and temperature gauges, fluid samplers, microseismic sensors, and distributed optical sensing cables.

Pressure sensing is one of the most studied and, arguably, most well established leakage detection methods for deep subsurface monitoring. A large number of analytical and numerical modeling

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works have been performed to quantify pressure anomalies resulting from focused leakage (e.g., from faults and abandoned wells) and diffusive leakage (e.g., from leaky caprocks) (e.g., Nordbotten et al., 2005; Cihan et al., 2011; Sun and Nicot, 2012; Sun et al., 2013b; Kang et al., 2014; Dempsey et al., 2014; Heath et al., 2014; Birkholzer et al., 2015). Major advantages of pressure sensing over other deep subsurface detection technologies include its (i) early detection potential; (ii) cost effectiveness; (iii) suitability for continuous, automated, long-term deployment; and (iv) suitability for optimal sensing or targeted monitoring (Jung et al., 2013; Sun et al., 2013a; Jenkins et al., 2015; Hu et al., 2015). Concerns over pressure sensing include its lack of sensitivity to "small" leaks and its proneness to noise interference, especially when deployed for monitoring CO_2 enhanced oil recovery (CO_2-EOR) reservoirs. Notwithstanding the large number of theoretical studies, relatively few field experiments have been conducted to date to demonstrate the effectiveness and limitations associated with the pressure-based leakage detection for carbon storage reservoirs. Here, a distinction is made between field experiments that are designed to quantify the effect of pressure responses to leakage and those that merely collect pressure data as side products. We refer the former category as active monitoring, while the latter as passive monitoring.

This paper presents results from a series of deep subsurface tests conducted recently at a CO_2-EOR field near Cranfield, Mississippi, USA. These tests were exclusively designed to investigate the feasibility of deploying pulse testing as a simple and cost-effective leakage detection technique. Pulse testing can be considered a special type of pressure transient testing. During pulse testing, the injection rate is varied periodically while reservoir pressure responses are continuously monitored in observation wells. The pressure data are then analyzed to characterize hydraulic communication between wells and to infer reservoir parameters. Although pulse testing has long been used in reservoir characterization, its use for monitoring the integrity of carbon storage formations is new and, as far as we know, has never been tested in the field. In the following sections, we present the background of our field study site, the experimental design and methodologies, field data interpretation, and discussion. Finally, lessons learned from the field experiment are summarized.

2. Background of study site

The Cranfield site has been used as a demonstration site for geologic carbon storage during the last seven years, under collaboration between the Southeast Regional Carbon Sequestration Partnership (SECARB) and Denbury Onshore LLC (Denbury). Oil and gas production originally started at the site in 1944. Gas recycling was used to maintain reservoir pressure until 1959, when the gas cap was depleted. By 1966, most of the wells had been plugged and abandoned. The reservoir remained idle until Denbury began CO_2 flooding for EOR in July 2008. The source of CO_2 was produced from a nearby natural source in Jackson Dome, Mississippi. The Cranfield site was originally selected by SECARB to develop the practice of "stacked storage," which would use the EOR operations to support infrastructure setup, characterization, and public acceptance for longer-term saline storage of CO_2 (Hovorka et al., 2013).

The Cranfield reservoir is a four-way structural closure (with a northwest-trending crestal graben) located about 3,010 m below ground surface. The reservoir formation comprises fluvial sandstones and conglomerates of the Cretaceous lower Tuscaloosa Formation, which is underlain by a regional unconformity on top of shales and sandstones of the Dantzler Formation. The regional confining zone overlying the reservoir is 60 m of the middle Tuscaloosa marine mudstone. The CO_2 injection interval at the Cranfield site is locally referred to as the D and E units, which range from 14 to 24 m in thickness and were deposited as part of a laterally continuous but internally complex fluvial formation comprised of fining-upward sandstones and conglomerates. Chlorite coatings appear to have preserved porosity and inhibited quartz cementation, but occluded permeability. The stacking facies pattern of point-bar and channel sand bodies as found in the D–E units can have a significant impact on flow and transport paths, as many previous studies have shown (Knudby and Carrera, 2005; Sun et al., 2008). The reservoir temperature is about 129 °C, and reservoir pressure before CO_2-EOR started is around 32 MPa, which is close to the original hydrostatic pressure in place. The dip of the reservoir interval ranges from 1 to 3 degrees. More detailed descriptions of the regional and site geology related to Cranfield can be found in Lu et al. (2012).

Many of the past research and development activities at the Cranfield site had been conducted at its Detailed Area of Study (DAS) site, which consists of three colinear wells, including one injector (CFU31-F1) and two monitoring wells (CFU31-F2 and CFU31-F3) (Fig. 1). These three wells will be referred to as F1, F2, and F3 in the rest of this paper. The surface separation distance between F1 and F2 is 69.8 m, and between F2 and F3 it is 29.9 m. The bottom-hole distance between F1 and F2 is 60 m; between F1 and F3 it is 93 m; and between F2 and F3 it is 33.5 m. F2 and F3 were completed with fiberglass casing to facilitate electrical resistance tomography (ERT) measurements and other well loggings during site characterization. Fig. 2 shows the vertical distributions of permeability and

Fig. 1. Areal view of the detailed area of study at Cranfield site (Lon: −91.141°, Lat: 31.564°), which consists of an injector (F1) and two monitoring wells (F2 and F3). During leak experiments, F3 was used as a "leaky" well. Locations of the flowback tank and trailer area are also labeled.