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Overview of the CO2CRC Otway residual saturation and dissolution test

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Abstract

Residual and dissolution trapping are important mechanisms for secure geological storage of carbon dioxide. When appraising a potential site, it is desirable to have accurate field-scale estimates of the proportion of trapping by these mechanisms. For this purpose a short single-well test has been conceived that could be implemented before large-scale injection. To test this concept in the field, a residual saturation and dissolution test sequence was conducted at the CO2CRC Otway site during 2011. The test involved injection of 150 tonnes of pure carbon dioxide followed by 454 tonnes of formation water to drive the carbon dioxide to residual saturation. A variety of methods for measuring saturation were applied to the injection zone so the results could be compared. Here we provide an overview of the field-test sequence and the measurement methods.

Residual trapping; dissolution trapping; field measurement; CO2CRC Otway Project.

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1. Introduction

Residual and dissolution trapping are important mechanisms in carbon dioxide storage. Both mechanisms provide storage security removing the possibility of buoyant migration to shallower depths. Furthermore, even when structural trapping is used as the major trapping mechanism, residual saturation and dissolution can have a significant impact on the migration and lateral extent of an injected plume, and the ultimate available storage volume in the formation.

Given their importance, it is desirable to be able to make reliable estimates of the expected residual and dissolution trapping at a given site. While some estimates can be made from laboratory core testing, possible bias from sample selection and the issue of scale-up need to be addressed. Thus there is a strong motivation to have field-scale tests that can measure residual and dissolution trapping at the appraisal stage when evaluating a potential storage site.

Various methods have been developed for measuring residual saturation of oil and gas [1-5]. These serve as a starting point for measuring residual carbon dioxide, but there are some significant differences that require consideration. First of these is that residual hydrocarbon results from water flooding of a large accumulation that has been in place for a long time with an expected horizontal lower boundary that has been gravity stabilised. In contrast, short-term injection of carbon dioxide will involve a buoyant plume that may not contact all of the rock volume adjacent to the injection interval. In addition, carbon dioxide has different physical and chemical properties to oil and gas, including much higher solubility, so these properties need to be accounted for when modifying methods for petroleum.

With these considerations, a field-testing program was undertaken at the CO2CRC Otway Project site during 2011 to measure residual and dissolution trapping. This paper provides an outline of this field-testing program.

2. The injection site and interval

The CO2CRC Otway site has previously been used for the injection of 65,445 tonnes of CO_2-rich mixture into the Waarre-C Formation (Stage 1) [6]. For this earlier stage, injection was via the CRC-1 well with injection at a depth of 2,003 – 2,014 m TVDSS (true vertical depth below mean sea level). The next stages at the CO2CRC Otway site involved drilling a new well, CRC-2 (Stage 2A) and the residual saturation and dissolution test (Stage 2B), the subject of this paper, conducted in 2011. Provisions have been made for possible future tests at the site.

The residual saturation and dissolution test involved injection into the Paaratte Formation at between 1392-1399 m TVDSS, approximately 600 m shallower than the earlier first storage demonstration. The Paaratte Formation represents a saline aquifer that is typical of many prospective geological systems under consideration for future commercial-scale CO_2 storage. It has no apparent structural closure and is lithologically heterogeneous. Deposited in a shallow marine deltaic setting with dominant fluvial and tidal processes, the preserved sediments comprise intercalations of medium to high permeability sands thinly interbedded with carbonaceous mud-rich lithologies, and are over printed with diagenetic carbonate cement layers which serve as seals of varying quality. The injection interval was selected within a relatively homogenous sandstone unit between two cemented sandstones. It has an average porosity of 0.28 and an average permeability of 2.1 darcies. The bounding cements comprise over 30% grain coating dolomite that has occluded the pore space and reduced the porosity to 0.05–0.10 and permeability to 1–10 millidarcies. This has the effect of vertically confining the injected fluid in the vicinity of the perforation interval.

The entire test sequence was conducted between June and September 2011 with most of the time devoted to detailed characterisation, both before and after injection. Over a four-day interval 150 tonnes of pure CO_2 was injected. Then to drive the CO_2 down to residual saturation 454 tonnes of water was injected following the CO_2. This water was produced from the injection horizon before the start of the test and stored in tanks at the surface.

3. Surface facilities and downhole configuration

Surface facilities included tanks with capacity to hold up to 600 tonnes of water produced from the formation. Using formation water has the advantage that the water chemistry is already matched to the formation, plus it avoided the need to supply water by pipe or trucks. A photograph of the surface facilities is included in Fig. 1.

Fig. 1. The surface layout at the Otway Project site. The CRC-2 wellhead is left of centre, the CO_2 storage tank is at right and water pipes are in the foreground. The water storage tanks are out of the frame to the right.

The CRC-2 well was completed with 0.140 m (5.5 inch) outer diameter production casing and 0.0253 m (1.0 inch) internal radius tubing. Installed downhole was an inflatable straddle packer, configured to isolate the test zone and isolate the sump area. Redundant sets of pressure/temperature gauges were installed at the top and bottom of the perforated interval, along with a fiber-optic distributed temperature sensor and heat-pulse conductors. An additional two retrievable memory gauges were installed at 900 and 1047 m TVDSS and retrieved using slickline. A U-tube sampling system was installed at the top of the perforated interval to provide representative fluid samples under in situ pressure conditions.

To produce water, an artificial gas lift method was employed with injection down the casing annulus into the tubing via a mandrel at 948.7 m TVDSS. At the surface produced gas and water was first admitted into a degassing tank where any excess gas from solution was vented. The 454 tonnes of injected water that displaced the CO_2 to residual saturation was saturated with CO_2 to avoid dissolving the residual trapped CO_2. Pure CO_2 was pumped through an injection line connected to a mandrel located at 798 m TVDSS to mix with injected water at a ratio determined by pressure and temperature conditions at the perforations.

4. The test sequence

The test sequence is shown in Fig. 2. Prior to the test sequence, 510 tonnes of formation water were produced over 10 days. The testing started with initial characterisation of the formation without CO_2. Carbon dioxide was injected followed by further characterisation, then formation water was injected to drive the CO_2 to residual saturation, and a series of tests were implemented to measure saturation. These methods for measuring residual saturation are briefly described below.

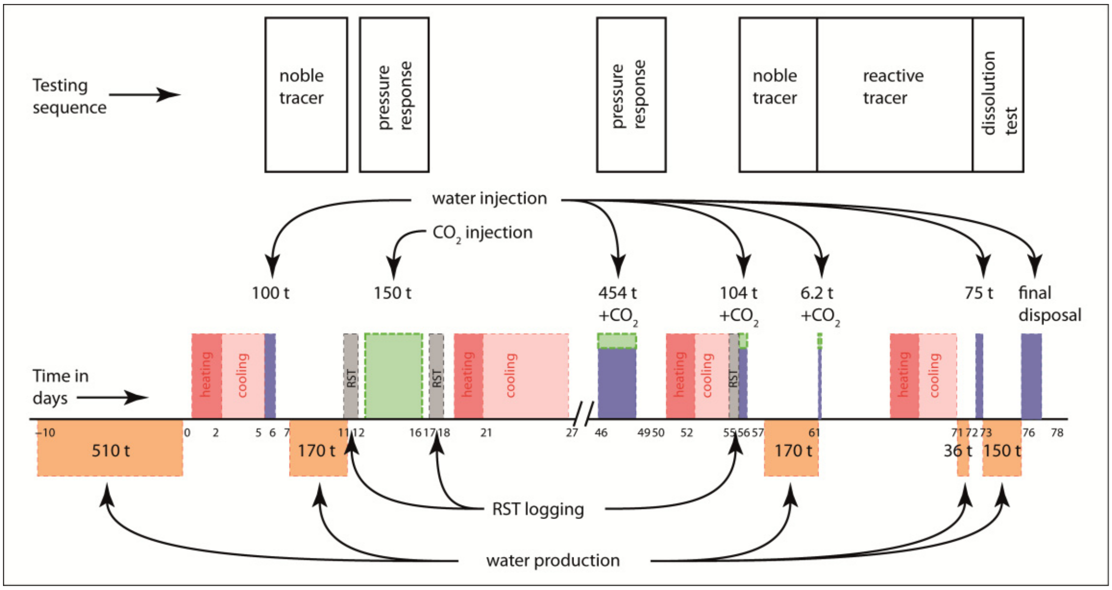

Fig. 2. Sequence used in the residual saturation and dissolution test.

4.1. The pressure response

High-quality pressure data were obtained from the downhole gauges, these data are plotted in Fig. 3. Each step involving injection or production was analysed. Prior to the CO_2 injection, the single-phase water injection and production was interpreted using conventional well test analysis for bulk permeability. This also enabled determination of the duration of wellbore storage and measurement of a negative skin resulting from the perforations. After CO_2 injection the pressure responses involve two-phase flow. Essentially this requires multi-phase well test analysis where numerical simulation is used to inverse model the reservoir response to derive the residual saturation. The principles of this method are described in detail in Zhang et al. [7].

The results of radial simulations are shown in Fig. 4 (using TOUGH2 with EOS7c and hysteretic relative permeability curves) matched to the downhole pressure data and using the surface measurements for the rates of injection and production of water and CO_2. The left-hand panel shows the simulated CO_2 gas saturation at the end of CO_2 injection, where the combination of the gravity override and higher CO_2 injection rates in the upper part of the perforations causes the CO_2 in the reservoir to be mainly in the top 2–3 m. The right-hand panel in Fig. 4 shows the distribution of residual CO_2 after the end of injection of water pre-saturated with CO_2. For these fits the residual gas saturation varies across the reservoir (since it depends on the history of the gas saturation), but is generally below 0.2.

4.2. Measuring hydrogen index using a pulsed neutron logging tool

On three occasions during the test sequence a reservoir saturation tool (RST) was used to log the well over a 255 m interval. Logging was conducted prior to CO_2 injection, after CO_2 injection, and after water injection at residual saturation conditions. Comparing these logging measurements allows the CO_2 saturation to be determined at each step. The tool's depth of investigation is rated at 0.25 m with a vertical resolution of 0.38 m.

Due to the low salinity of the formation water (approximately 800 ppm), thermal decay porosity (TPHI) was used as the main measurement for calculating saturation. From the logging results, residual saturation was determined to be around 0.18 in the lower half of the perforated interval and around 0.23 in the top half. An issue for the interpretation of the data was the changing fluid conditions in the wellbore as the tool had not been characterised for operating when immediately surrounded by CO_2.

4.3. Thermal testing

In the thermal test temperature is recorded using a fibre-optic heat-pulse sensor. The heat-pulse sensor consists of a borehole length heater and a fiber-optic distributed temperature sensor (DTS). To observe changes in thermal properties the heater is used to create a thermal pulse. The decay of the thermal pulse is then used to estimate a thermal diffusivity. The depth of penetration into the formation is 1–2 m, significantly greater than the pulsed neutron logging [7].

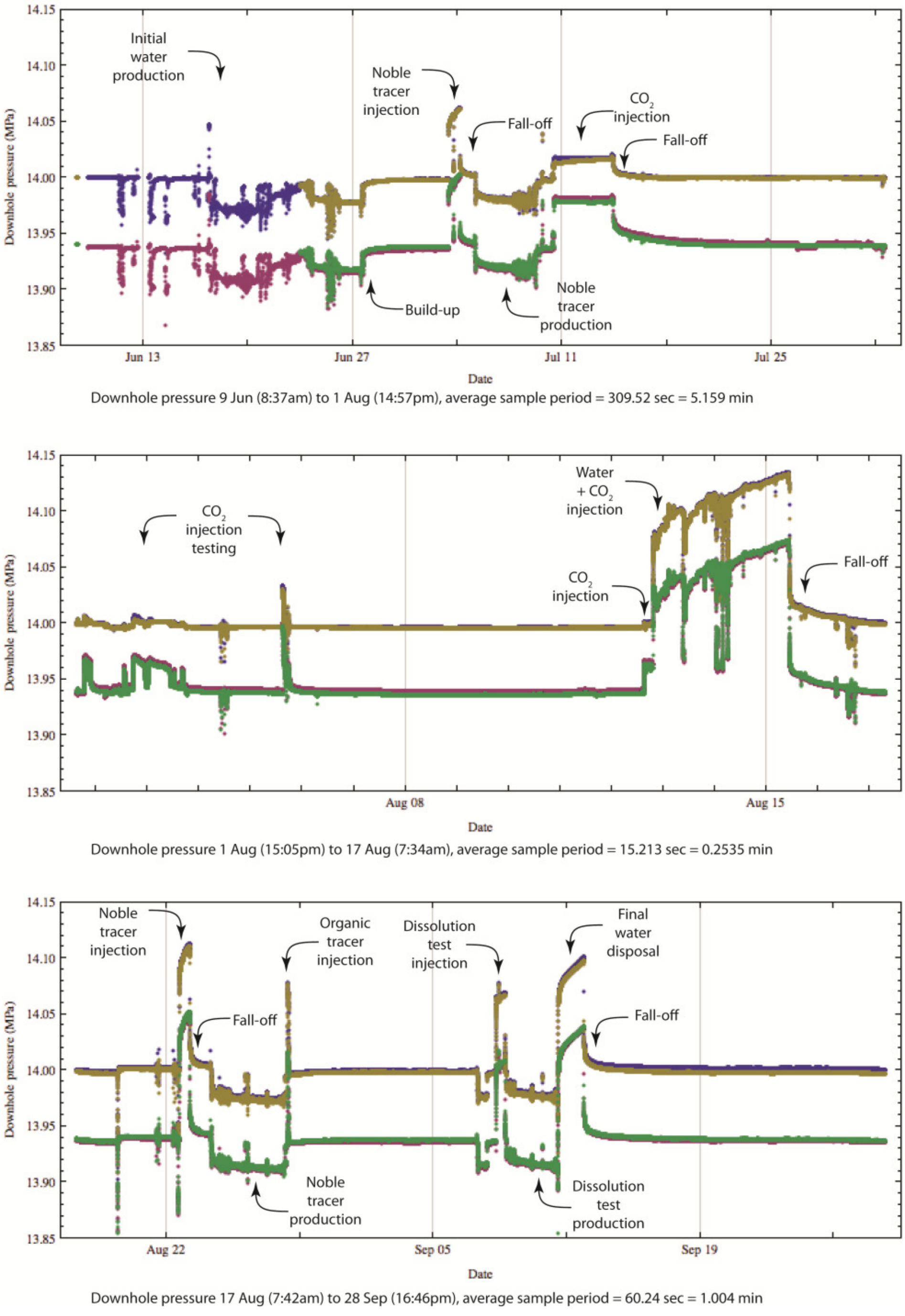

Fig. 3. Downhole pressure measurements during the entire test sequence. All four permanent gauges are plotted with the two gauges below the injection interval displaying higher pressure values than the two gauges above the injection interval. The pressure difference across the injection interval can be seen to be smaller when lower-density carbon dioxide is present.

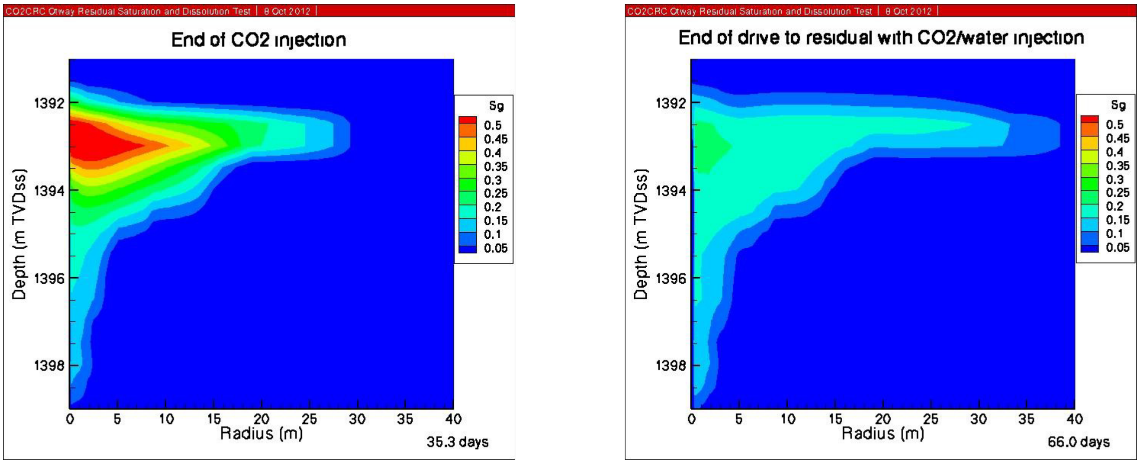

Fig. 4. Radial simulations (based on fits to field pressure data) of the distribution of gas saturation during the test. On the left is the snapshot at the end of CO_2 injection. On the right is the distribution of residual CO_2 at the end of the injection of CO_2-saturated water. Times are from June 11, 2011, 7:55 (the start of initial water production).

4.4. Noble gas tracer testing

Partitioning tracers can be used to estimate residual-phase saturation [7]. Single-well partitioning tracer tests are more difficult to interpret than reactive tracers, because there is no separation between the timing of peaks of more and less partitioning tracers. Instead the increased spread of the production peak of the partitioning tracer as compared with that of the non-partitioning tracer is used to calculate residual phase saturation. At Otway the noble gases krypton (Kr) and xenon (Xe) were injected with water before CO_2 injection to act as non-partitioning tracers. Then Kr and Xe were injected again after residual saturation was obtained to act as partitioning tracers.

4.5. Reactive ester tracer partitioning

Numerous field measurements of residual oil have been undertaken using ester tracers (ethyl acetate). In this single-well tracer technique, a tracer dissolved in formation water is injected into the formation. In the presence of oil, ethyl acetate will hydrolyse to form ethanol, a secondary tracer. When the well is produced, the concentration profiles of the two tracers are monitored. As a consequence of different oil-water solubilities, the ethanol selectively partitions into the aqueous phase and returns to the well earlier than ethyl acetate. The difference in the arrival times can be used to determine residual oil saturation.

Carbon dioxide reacts differently to oil, so the standard reactive tracer test needs to be modified. A laboratory-based testing program by Myers et al. [8] identified triacetin, propylene glycol diacetate and tripropionin as suitable reactive esters to use with carbon dioxide, so these were included in the Otway test sequence.

A challenge for the carbon dioxide test is that carbon dioxide is more water soluble than oil, so the injected water needs to be saturated with carbon dioxide to prevent dissolution of residual carbon dioxide during the test. In practice maintaining the low injection rate of carbon dioxide for the short period required for this part of the test proved to be problematic, and a better design for the surface component of the injection facilities would help in future implementation of this test.

4.6. Dissolution testing

A field method for measuring residual gas saturation has been developed by Bragg et al. [2]. In this method, gas-free formation brine is injected into a well to dissolve the residual gas from a region around the wellbore. The brine is then produced from the well. The gas content of the returning water is measured and from this the residual gas concentration can be calculated.

This test is readily applied to carbon dioxide, especially as carbon dioxide is more soluble than methane. The test has an advantage over other methods in that there is no need to mix carbon dioxide into the injected steam to produce saturated water. However, in comparison to other methods this test is destructive in the sense that the residual phase is removed and so further testing cannot be performed. For this reason it was placed at the end of the test sequence. Details of this part of the field test are described by Haese et al. [9].

4.7. Laboratory core testing

Measurements on a cylindrical core sample from the injection interval in the Paaratte Sandstone are described by Krevor et. al. [10] This vertically-oriented sample has length 9.5 cm, porosity 0.28 and permeability 1.156 darcies, slightly lower than the injection interval average. The maximum trapped carbon dioxide saturation was observed to be 0.33. It was noted that because flooding was perpendicular to the bedding planes that several flow barriers caused local spikes in carbon dioxide concentration. Stratification in sedimentary rock has been observed to result in different residual saturation values for horizontal and vertical flooding in laboratory tests [11]. A lower value of residual saturation with flow parallel to the bedding would be consistent with field observations at Otway where flow is predominantly horizontal in the bedding plane.

5. Conclusions

The CO2CRC Otway project successfully injected CO_2 and drove it to residual saturation. Several measurements of residual trapping were deployed, each with a different volume of investigation. In principle, all of the methods deployed could be used to measure residual trapping, although some of the methods would benefit from further development and analysis. The importance and duration of thermal effects has been identified as an important component for detailed study.

Previous studies with residual oil concluded that more than one method should be used for the most accurate determination [3], and the same conclusion applies here for residual CO_2. As with oil [4], each technique offers advantages and limitations. Detailed reporting on each method is in progress for separate publication.

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