CONFERENCE PROCEEDINGS

Technologies for Measuring Well Integrity in a CO_2 field

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Abstract

In the United States carbon capture and storage as a means of emissions mitigation is moving towards commercial implementation. In anticipation of large numbers of CCS sites coming online it is important to identify existing technologies that can measure and monitor the integrity of wells that are exposed to CO_2. Well integrity is important because wells and the annuli and pathways that may exist within them can act as leakage pathways for CO_2 back to the surface or as conduits for leakage between formations.

Because oil and gas wells are typically a series of nested casings and well cement a variety of measurements is necessary to study the integrity of a well. These measurements can be acquired using wireline tools such as caliper and ultrasonic tools to measure the integrity of the casing, sonic and ultrasonic tools to measure the integrity of the well cement, and tools to sample the casing, cement, and formation and formation fluid. This paper describes the tools and methods that can be used to investigate the integrity of a well, describes how the integrity of a 30 year old CO_2 production well was measured, and makes suggestions for what techniques should be used in the future.

Introduction

In the United States carbon capture and storage as a means of emissions mitigation is moving towards commercial implementation. In the next several years the seven DOE partnerships may be starting injection projects in addition, other government and commercial CCS projects are also expected to come online. In anticipation of large numbers of CCS sites coming online it is important to identify existing technologies that can measure and monitor the integrity of wells that are exposed to CO_2. Well integrity is important because wells and the annuli and pathways that may exist within them can act as leakage pathways for CO_2 back to the surface or as conduits for leakage between formations. The information in this paper is presented with the intention of giving both technical and other professionals involved with the planning of CCS and well integrity projects an introduction to the current tools and measurements that may be used to conduct a well integrity study.

Oil and gas wells are typically a series of nested casings and well cement. Figure 1 shows a schematic of a “typical” well showing the nested nature of the casings and cement. Figure 2 shows a schematic of the leakage pathways that can exist within a well. Because there are many different possible leakage pathways within a well it is necessary to examine the condition of the casing and the cement and identify any annuli or defects that exist within the well. There is no one tool or method capable of looking at all of these features at the same time, so a suite of measurements must be run to analyze the integrity of a well. These measurements can be acquired using wireline tools such as caliper and ultrasonic tools to measure the integrity of the casing, sonic and ultrasonic tools to measure the integrity of the well cement, and tools to sample the casing, cement, formation, and formation fluid. This paper will (1) give a brief introduction to the methods that can be used to collect information about the integrity of a well, (2) describe a comprehensive suite of cased-hole logging and mechanical integrity tools that was recently used to investigate the integrity of a 30 year old CO_2 production well and discuss the value of the tools for the assessment, (3) make recommendations for measurements in future experiments, and (4) suggest what might be considered as minimum measurements for commercial projects.

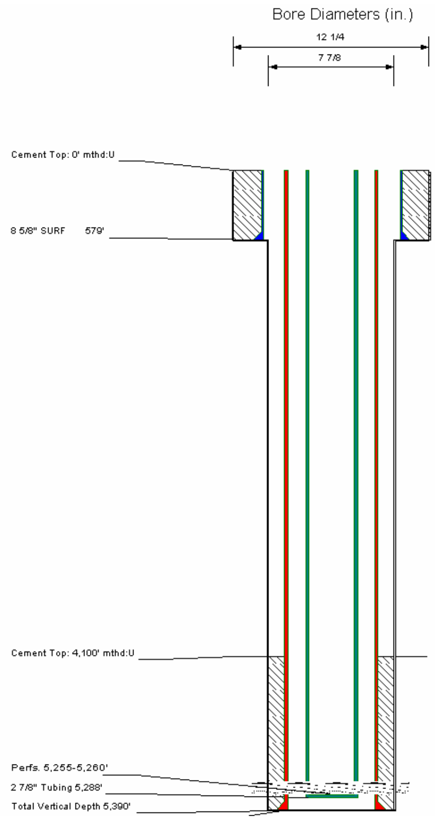

Figure 1 Typical oil or gas well Showing the surface casing (blue), the production casing (red), and the production tubing (green). The cemented sections are crosshatched. [Colorado Oil and Gas Conservation Commission, 2007]

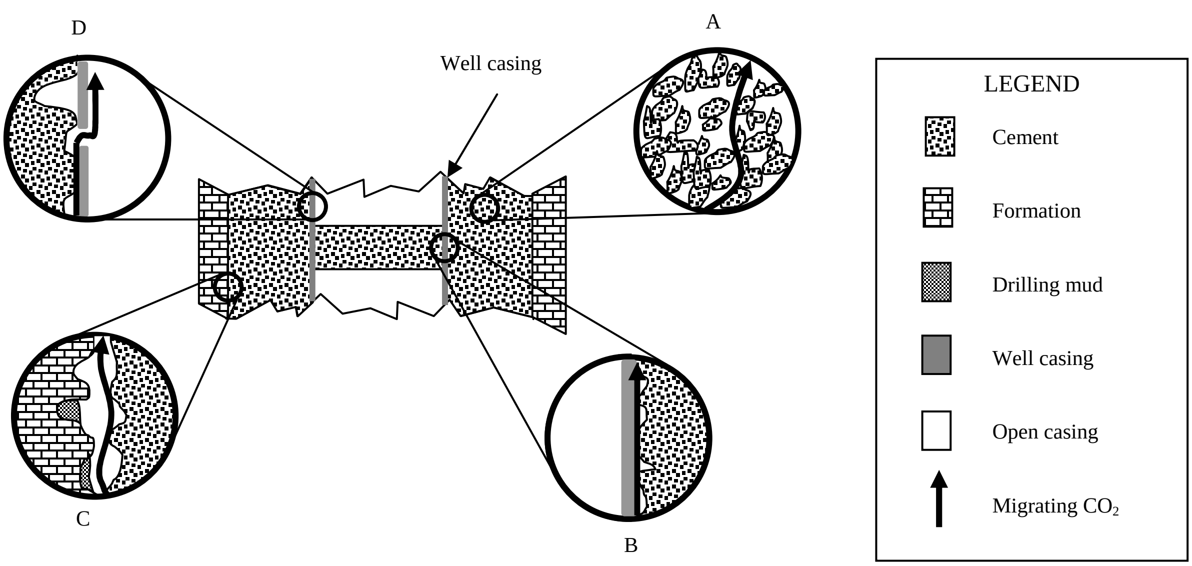

Figure 2 (A) CO_2 migration through the pores or pathways of the well cement. (B) CO_2 migration through annuli or defects that exist between the casing and the cement. (C) CO_2 traveling through an annulus or pathway at the interface between the cement and the formation. (D) CO_2 entering the wellbore through a damaged casing and traveling up the inside of the well. Note, if the well has not been abandoned there will be no plug. [Adapted from Duguid, 2006]

Tools for measuring well integrity

Existing wells are typically cased and cemented during construction, so tools to investigate them need to be able to investigate the integrity of the casing, the cement, the bond between the casing and the cement, and the bond between the cement and the formation. The tools that may be used to measure integrity can be split up into (1) logging tools that do not physically change the well in any manner (non destructive) and (2) sampling or testing tools that do cause, even if minor, a physical change to the wellbore. Logging tools for wellbore integrity include multifinger caliper tools, sonic bond tools, ultrasonic logging tools. Sampling and testing tools include cased-hole mobility and fluid analysis tools, and sidewall coring tools.

Logging tools

The logging tools described in this section are used to examine the well without causing any permanent changes to the condition of the well. These tools are used to examine the condition of the casing, the interface between the casing and the cement, the cement, and the interface between the cement and the formation.

Multifinger caliper tools

A caliper tool is a tool with multiple fingers protruding radially from the body of the tool. The fingers are used to measure the internal radius of the well in 360° to an accuracy of +-0.05 inches. Multifinger caliper tools can be used to measure the internal diameter of casings between 1 ¾ inches and 13 3/8 inches. [Schlumberger, 2004] Changes in the internal radius can indicate corrosion, wear, or other damage in the wellbore.

Although multifinger caliper tools give information on the condition of the inside of the casing they cannot provide information on the condition of the outside or the thickness of the casing. Further information on the use of multifinger caliper tools and the visualization of the multifinger caliper data can be found in papers by Oliver [2005], and Julian et al. [2007]. Figure 3 shows examples of a caliper tool. Figure 4 shows a 3-D presentation of caliper data showing a damaged casing. Figure 5 shows a typical log readout from a caliper tool.

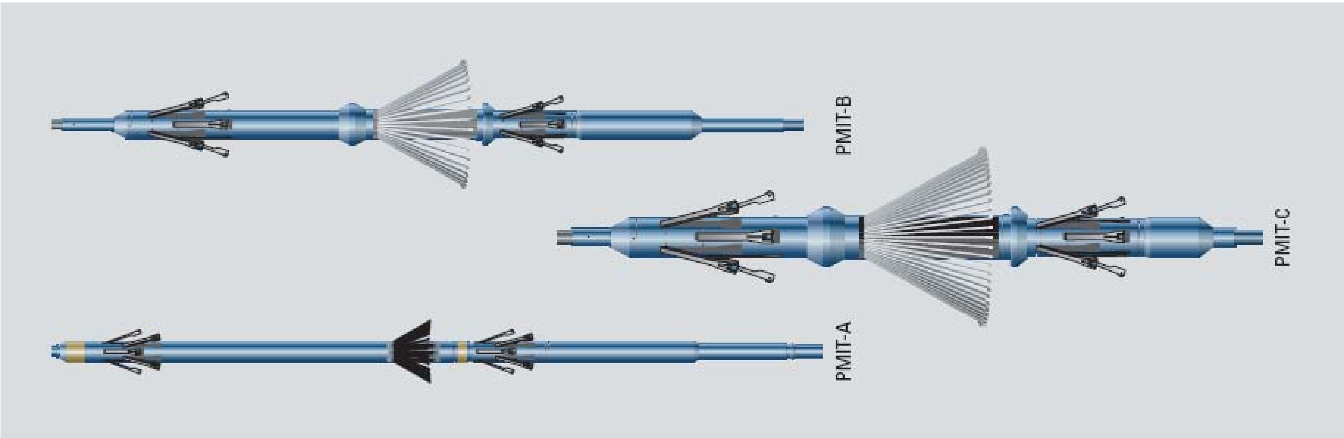

Figure 3 Examples of caliper tools used to measure the inside diameter of a well. Image courtesy of Schlumberger.

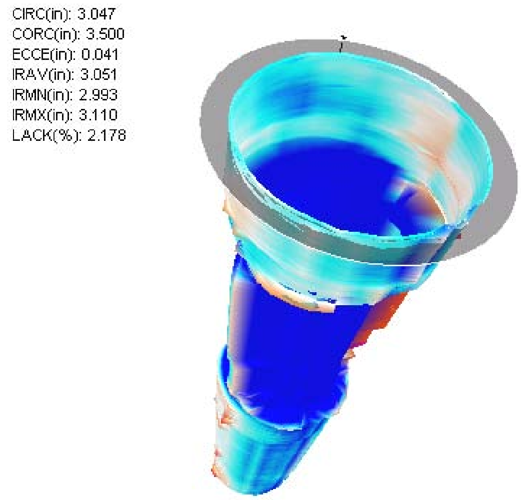

Figure 4 A 3-D presentation of caliper data showing a damaged casing (dark blue). Image courtesy of Schlumberger.

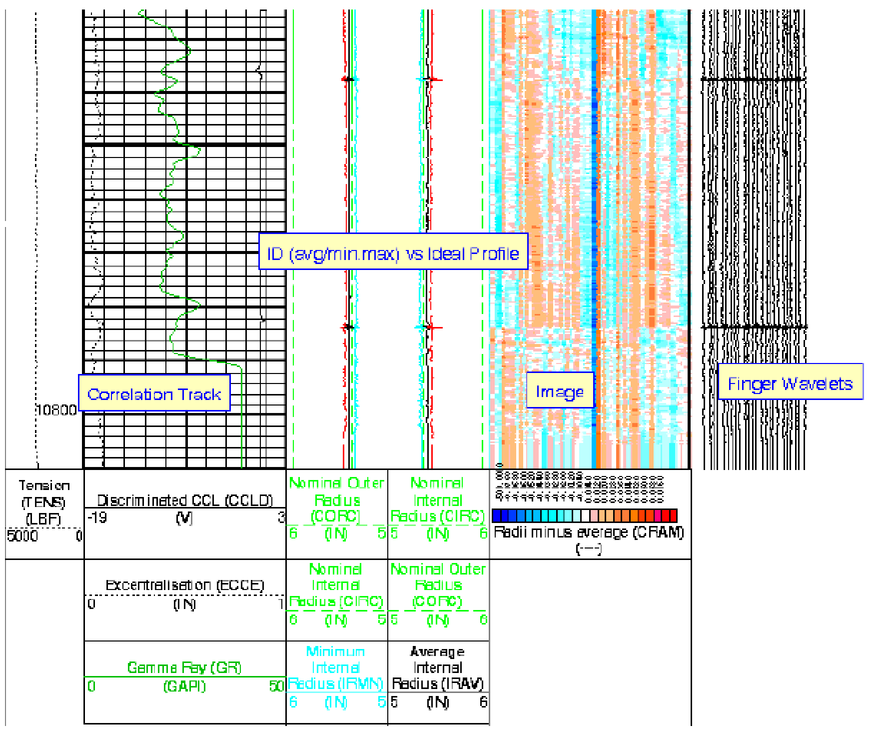

Figure 5 Typical log presentation of caliper data showing the correlation track (used to correlate the log to other logs), the inside diameter track (ID), the image track, and the finger wavelet track. Image courtesy of Schlumberger.

Sonic bond tools

Sonic bond tools or cement bond tools transmit a signal through the well to the casing and formation and then measure the magnitude and transit time of the refracted signal. The strength and transit time of the refracted signals provide information about the bond between the casing and the cement, the density of the cement, and the bond between the cement and the formation.

Sonic bond tools typically provide information on the cement bonds within the well using two metrics. One metric, called the bond index, gives a quantitative estimate of the cement to casing bond. A casing with a bond index over 0.80 (on a scale from 0 to 1) over distance dictated by the casing diameter is normally considered to have good zonal isolation. The bond index calculation is based on the amplitude of a sonic wave attenuated within the wellbore, the amplitude of the sonic wave attenuated by an uncemented casing, and the theoretical amplitude of a sonic wave if there is a 100% casing-to-cement bond. The other metric, called a variable density log, is a presentation of the magnitude of the actual waveform measured at the receiver. This measurement gives qualitative information on both the casing-to-cement bond and the cement-to formation bond.

In a well with a good bond between the cement and casing the transmitted sound waves will be attenuated when the signal returns from the well to the receiver. In a well with a poor cement-to-casing bond the returning signal will show little attenuation.

Sonic bond tools tend to work well in most fluids that may be encountered within a wellbore and are not affected by the ruggosity of the casing. Both the bond index and the variable density log measurements look at the average bond between the cement and the casing and do not identify specific pathways of locations (radially) where there may be a poor bond. Furthermore in areas where a high amplitude (poorly attenuated) wave is measured there will be ambiguity as to the cause because the measurements are sensitive to fast formations, liquid filled microannuli, and contaminated cements. Lastly a dry microannulus can still allow high attenuation although there is not zonal isolation. Boyd et al. [2006] and Hayman et al. [1991] provide further information on sonic bond tools. Figure 6 shows a schematic of a sonic bond too and Figure 7 shows a typical log presentation of sonic bond data.

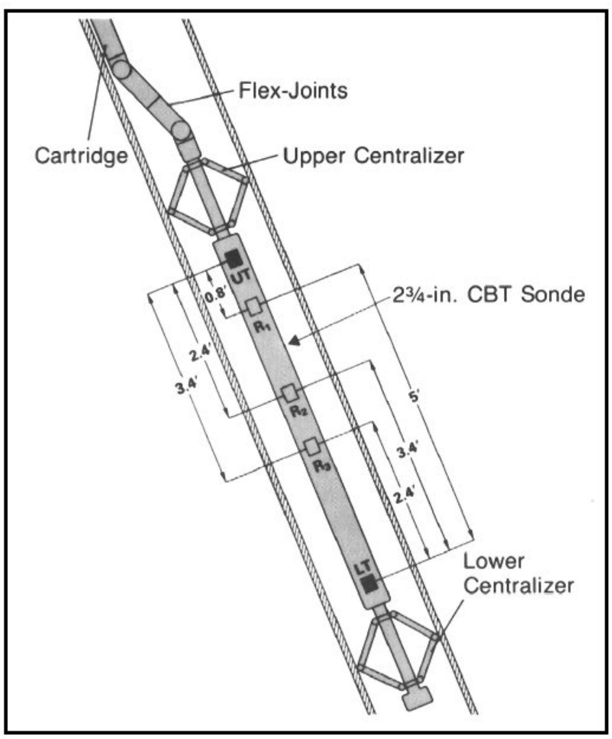

Figure 6 Schematic of a cement bond tool showing spacing between the transmitters (UT and LT) and the receivers (R1, R2, and R3). Image courtesy of Schlumberger.

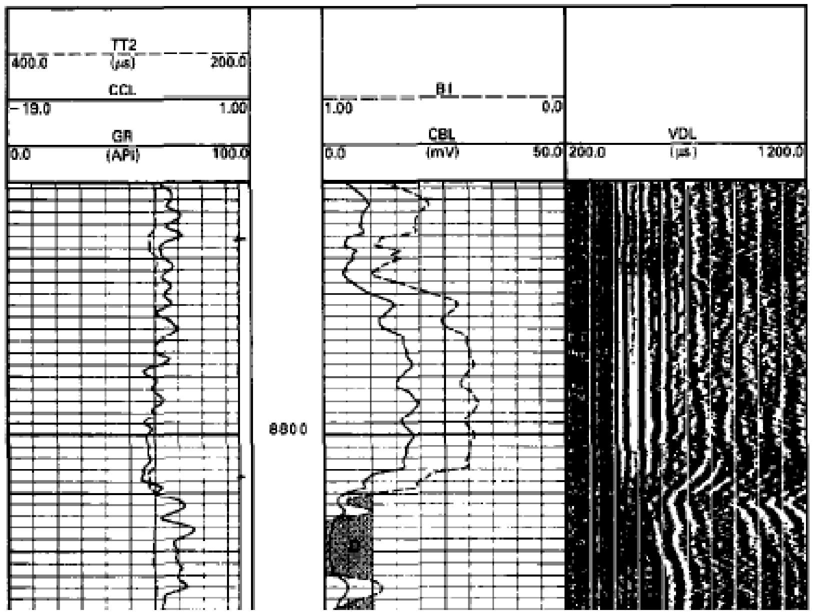

Figure 7 Typical cement bond log showing the correlation track (left), the bond log and bond index track (center) and the variable density log (right). Image courtesy of Schlumberger.

Ultrasonic logging tools

Ultrasonic tools also use sound waves to investigate the integrity of the well. The tools use ultrasonic waves to measure the internal condition of the casing, the internal radius of the casing, the thickness of the casing, and the acoustic impedance of the material outside the casing. Ultrasonic measurements also provide information on the interface between the cement and casing. Furthermore, the most recent generation of ultrasonic tool can provide information on the next interface, which in many cases is the cement–formation interface but could also be another cement-casing interface. The acoustic impedance of a material is a product of the acoustic velocity and density of the material. From the acoustic impedance of the material outside the casing the can be classified into cement, microdebonded cement (has a microannulus between the casing and the cement), liquid, or gas. Unlike the sonic tools already discussed ultrasonic tools can image the well in 360 degrees so specific pathways or debonded areas can be identified.

The advantage of using ultrasonic tools is that they can provide information on the condition of the casing and the cement within the same pass, they provide a detailed image of the well, and they can differentiate different types of materials behind the casing. Also, like the tools already discussed ultrasonic tools are nondestructive.

The success of ultrasonic measurements within a well is limited by the condition of the casing and the condition of the wellbore fluid. Both of these are particularly important in existing wells the casing may have been exposed to fluids or operations that damaged the casing. The wellbore fluid needs to be clean and consistent in order to estimate the acoustic impedance of the fluid.   It is not uncommon for old wells to have significant “junk”& sediment in them that is difficult to clean out. In a recent project that used an ultrasonic evaluation tool, chunks of material were basketed from the wellbore and despite attempts to clean the wellbore fluid the wellbore fluid properties measurement made during the descent showed the fluid properties to be erratic and difficult to characterize. Thus it is important that in all future projects ample time is devoted to cleaning the wellbore fluid to ensure that the fluid properties measurement is successful. The fluid properties measurement is necessary to properly calibrate the results of the ultrasonic measurement. Further information on ultrasonic logging tools can be found in work by Nelson and Guillot [2006] and van Kuijk et al. [2005]. Figure 8 shows a schematic of an ultrasonic wave being reflected and transmitted within a well, Figure 9 shows picture of an ultrasonic imaging tool, and Figure 10 shows a typical log output for an ultrasonic tool.

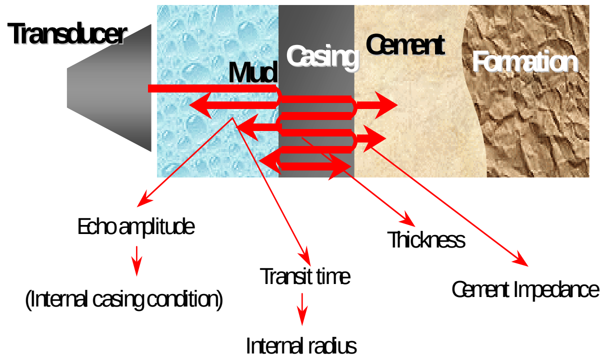

Figure 8 Schematic of the reflections of an ultrasonic wave being transmitted from a tool to the various surfaces that make up a well showing what parts of the reflection are used to gather information about the different layers within a well. Image courtesy of Schlumberger.

Figure 9 Diagram of an ultrasonic imaging tool showing three different transmitter/receiver units. Image courtesy of Schlumberger.

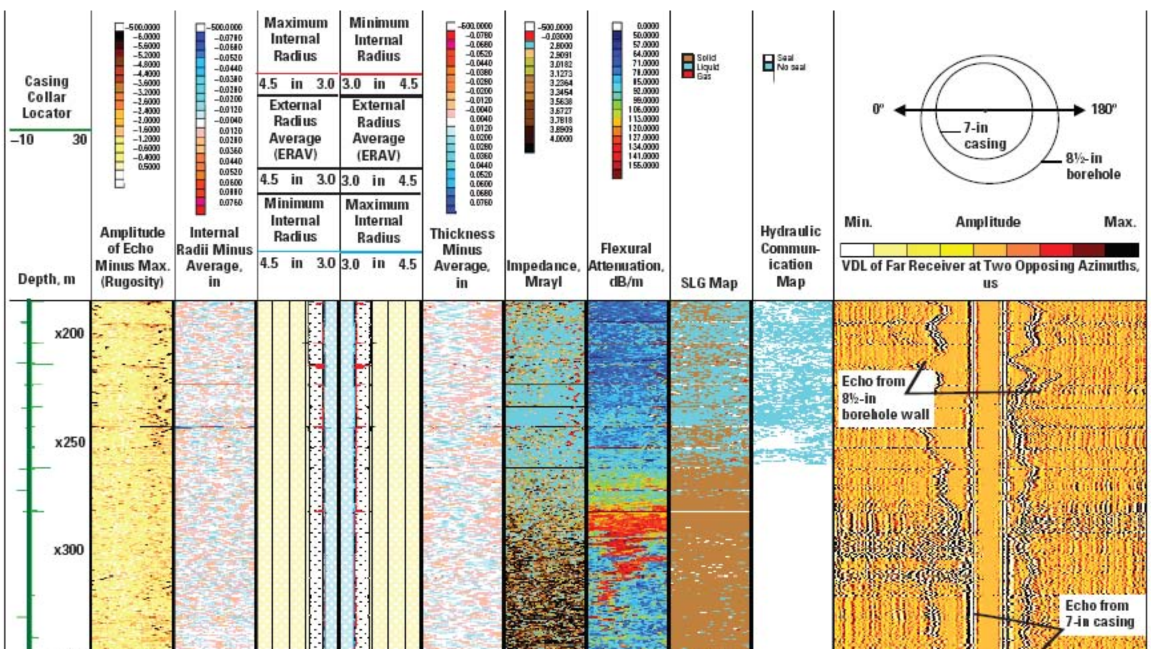

Figure 10 Log presentation of ultrasonic data including a presentation of the internal casing radius, the casing thickness, a solid (cement), liquid and gas map of the material outside the casing, and a map of the casing with respect to the borehole showing eccentralization. Image courtesy of Schlumberger.

Sampling and testing tools

Cased-hole mobility and fluid analysis tools

Measurements of the cement and formation permeability can be performed in situ using tools that can drill through the casing, draw down the pressure on the newly exposed material, and measure its response. This drawdown test is sometimes also referred to as a pretest. From the pretest the mobility and permeability of the material can be calculated. We will not delve into the mathematics of the mobility calculation in this paper for further details on the mobility calculation the reader is referred to SPE paper 72371 [Burgess et al., 2001]. Because cased hole mobility tools are stationary during drilling and testing it is possible to have multiple tests through the same point in the casing where the hole in the sidewall is made deeper between tests and changes in mobility of the cement and/or formation can be measured. It is also possible to take fluid samples through the hole in the casing using a fluid sampling module to analyze the formation fluid in situ and to collect and retrieve it for further laboratory analysis.

Although cased-hole mobility and fluid analysis tools offer the advantage of in situ mobility measurement, in situ fluid identification, and in situ pH measurement and physical sampling the mobility measurement and the fluid measurements, including the samples collected, can be complicated by the completion history of the well. Fluids that have been present in the wellbore during completions over the life of the well can impact formation properties and sampling capability. Open perforations and depleted formations can also present a significant challenge as they may take in wellbore fluids that can complicate fluid analysis. Furthermore, although cased-hole mobility tools are capable of plugging the hole left in the casing they cannot plug the hole in the cement and formation so they do damage the well slightly by creating a pathway between the casing and the formation. Figure 11 shows an example of an in situ fluid sample log. Figure 12 shows a pressure versus time plot for a permeability measurement.

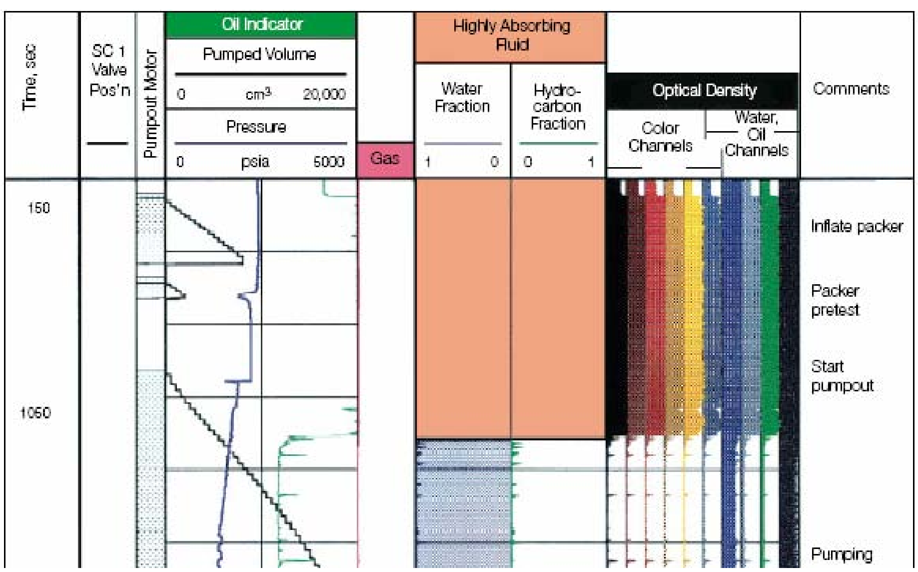

Figure 11 An example of a down-hole fluid analysis log. Image courtesy of Schlumberger.

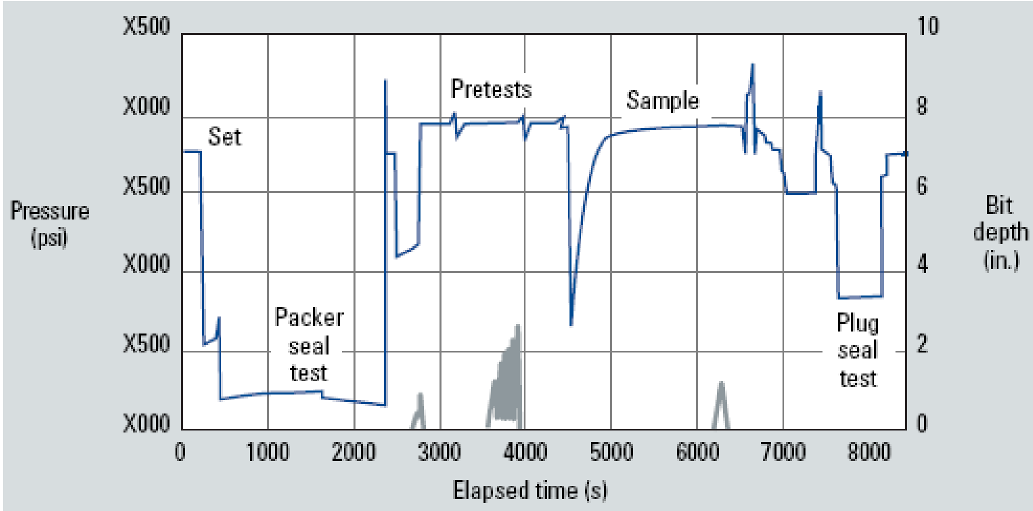

Figure 12 Pressure versus time (blue) and bit penetration versus time (gray) for a cased-hole permeability tool showing pretests and a sampling event. Image courtesy of Schlumberger.

Sidewall coring tools

Sidewall cores have been successfully removed from the first two wells where cased-hole sidewall coring has been attempted. Cased-hole sidewall coring tools have a special coring bit that is capable of cutting through the casing, the cement, and the formation and retrieving a composite sample, a core, containing each material. The samples are about and inch in diameter and a few inches long. The retrieval of sidewall cores allows the detailed inspection of wellbore materials for damage by micro characterization and microimaging techniques. The disadvantage of taking sidewall cores is that it is a destructive technique that leaves an, approximately, one inch hole in the side of the well. Figure 13 shows a photograph of a sidewall core that was recovered from a well at the RMOTC in conjunction with Princeton University's Carbon Mitigation Initiative. Figure 14 shows photographs of a sidewall core, and Figure 15 shows an SEM image of cement retrieved from the RMOTC well.

Figure 13 Two views of a cased-hole sidewall coring tool. The entire tool is pictured on the left and the sidewall coring unit of the tool is shown on the right. Photos courtesy of George Scherer, Princeton University.

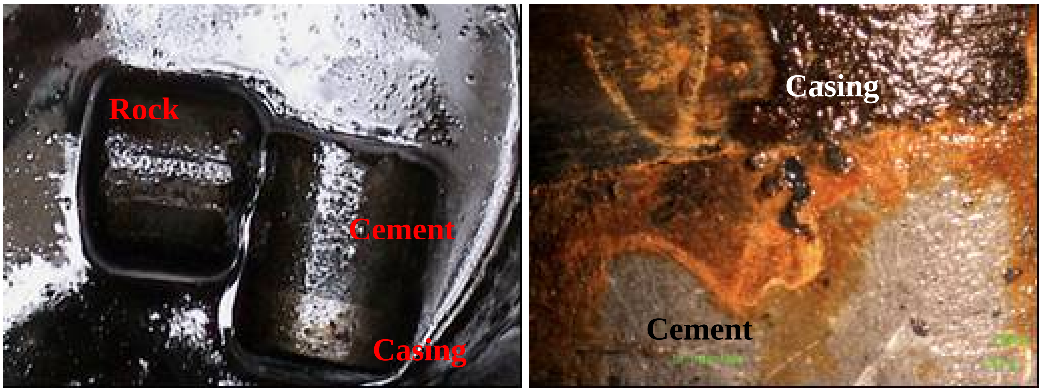

Figure 14 Sidewall cores retrieved from the RMOTC well showing the condition of the core as it is removed from the tool (left) and a cleaned core showing the cement-casing interface (right). Photos courtesy of George Scherer, Princeton University.

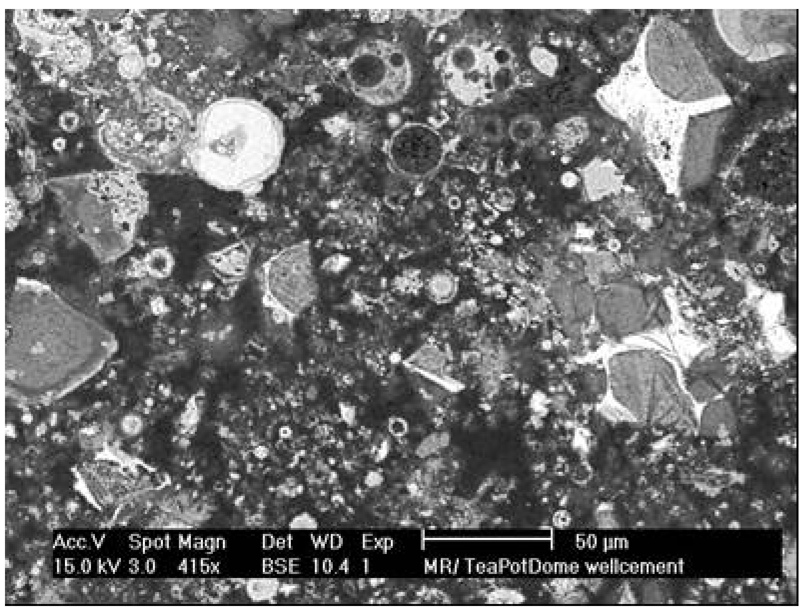

Figure 15 SEM image of cement recovered from the RMOTC well as part of Princeton University's Carbon Mitigation Initiative. SEM image by Mileva Radonjic, courtesy of George Scherer, Princeton University.

It is important to stress that each of the logging tools mentioned in this section provide different information about the integrity of the well and that the best overall view of the integrity of a well can only be achieved by using a combination of the tools. Caliper logs can not only be used to analyze the condition of the inside of the well they can be used to verify that an ultrasonic measurement is giving the correct casing radius providing information on the quality of the ultrasonic measurement. Also, differences between ultrasonic measurements and sonic measurements at the cement-casing interface can provide additional insight to the condition of the interface and the integrity of the well. Further combination the nondestructive logs with the physical testing and sampling techniques provides the opportunity to correlate physical and laboratory measurements with the different zones identified in the logs and gives the most complete picture of the integrity of the well. Although not specifically mentioned in this paper, it is important the run a temperature and pressure module in conjunction with the integrity logging tools to ensure that these conditions are recorded and can be factored into interpretation and modeling.

Recent field measurements

All of the tools described in this paper have been used extensively to investigate old wells. Recently the integrity of a 30 year old CO_2 production well was investigated using a suite of cased-hole logging and sampling techniques. The purpose of the experiment was to investigate the integrity of the well and the properties of the surrounding formations. The integrity of the production casing was examined using both multi-finger caliper and ultrasonic logging methods. Both methods were in agreement with respect to the condition of the casing. The condition of the cement and the bond between the cement and casing were investigated using sonic and ultrasonic logging tools. These measurements gave some information on the condition of the cement behind the casing and were generally agreement. The mobility of the cement and the surrounding formations was measured with a cased hole mobility tool that made measurements increasingly deeper penetration depth (in the sidewall) in the cement and then the formation. The technique gives good results in higher mobility areas but the sensitivity of the measurement, and our ability to quantify mobility ranges in less degraded cements is still under investigation. A cased hole sidewall coring tool was used to retrieve cores from both the production zone and the cap rock. The retrieval of cores made it possible to check the accuracy of the in situ mobility measurement and analyze the casing and cement for minor signs of CO_2 exposure that may not be evident from the other measurement methods.

Recommendations and requirements

For future wellbore integrity studies it is recommended that the logging and measurement program be similar to that of the 30 year old CO_2 well. The selection of well integrity tools should take into account the different leakage pathways identified in Figure 2. It is important to point out that the integrity measurements can be staged so that no unneeded measurements are run. This can be done running tools to log the casing prior to running tools to measure the integrity of the cement. The condition of the inside to the well should be logged using a multifinger caliper tool to look for damage and provide information on the possibility of a possible leakage pathway through the casing (Figure 2 D). If the caliper tool shows a heavily damaged casing the logging program can be halted and the well can either be repaired or plugged and abandoned. If the caliper measurement indicates that the casing has good integrity then ultrasonic and sonic logs should be run. Ultrasonic measurement of the well should also be incorporated into a measurement program to examine the thickness of the casing thus providing addition information on the existence or potential for pathways through the casing (Figure 2 D) and to provide data on the condition of the cement between the casing and formation and the nature of the interfaces (bonded or debonded) between casing and cement and cement and formation. Ultrasonic measurements add information on the leakage pathways shown in Figure 2 A, B, and C. It is important, when possible, to choose and ultrasonic tool that can provide information in the interface between the cement and formation as well as information on the interface between the cement and the casing. As mentioned earlier a sonic bond tool should also be run to examine cement integrity. The sonic tool will provide additional information on the potential leakage pathways at the cement interfaces, detailed in Figure 2 B and C, and sonic measurement will dovetail with the ultrasonic measurement to provide additional insight on the leakage pathways identified in Figure 2 A, B, and C.

Along with the non invasive techniques recommended so far, physical testing through the side of the well should also be conducted. Testing the mobility of the cement using a cased hole mobility tester is recommended because it will give real, in situ data on the mobility (permeability) of the cement. The cement permeability data provides data to calculate the speed a CO_2 would move if it were leaking through the cement matrix (Figure 2 A). Furthermore, if a fluid analyzer and sampler are used in conjunction with the mobility tester information on the composition and CO_2 content of the formation fluid can be collected. Finally, the last recommendation is to collect sidewall cores. Sidewall cores provide samples of the casing, the cement, and the formation and thus allow the physical inspection of the interfaces between the casing and the cement and between the cement and the formation. Because sidewall coring provides a sample of steel, casing, and the formation it can be used to provide detailed information, through the use of microscopic characterization and laboratory testing, on the potential for leakage through the casing, through the annuli at the cement interfaces, and through the cement (Figure 2 A, B, C, and D).

At a minimum the requirements for measuring the integrity of a single well should include multifinger caliper, sonic and ultrasonic logging tools. These tools are not destructive and can provide important information on the condition of the casing, the cement, and the interfaces between the cement and casing and the formation and cement. If a well is an existing well that is going to be abandoned or is to be used as one of several wells representative of a field of existing wells it is further recommended that at a minimum cased-hole mobility, fluid, and pH measurements are made and fluid samples are taken to ensure that the condition of the cement is well known and that the conditions that the well is exposed to are also well understood. These physical measurements can be used to develop of validate models of the well that may be used to further predict changes in wellbore integrity.

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