BOMS PROJECT

REVIEW OF
EXISTING MONITORING
TECHNOLOGIES FOR NEAR WELLBORE
MONITORING

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Preface/Acknowledgements

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CONTENT

1 EXECUTIVE SUMMARY

This report summarizes the current state-of-the-art regarding wellbore monitoring technologies, with a specific focus on those that could be useful for identifying near-wellbore leakage of CO_2. It is based on papers published in scientific journals, books and conference proceedings, publicly available reports from CCS operators, technical and promotional literature from service companies, and discussions with service companies and experts.

Particular attention has been paid to the use of downhole optical fibers for monitoring, since this is a rapidly advancing technology and may be especially useful for identifying CO_2 leakage. This is covered in Chapter 3, where we examine Distributed Temperature Sensing (DTS), Distributed Acoustic Sensing (DAS), Distributed Strain Sensing (DSS), and distributed Pressure Sensing (DPS) applications. We specifically examine the use of DAS as a receiver for 4D seismic surveys and for microseismic monitoring, as well as potential use as a direct chemical sensor. Finally, we look at some of the recent advances in data management and machine learning that are essential to make best use of the large volumes of data collected by optical fibers.

In Chapter 4 we look at various wireline logging tools that are commonly run in cased boreholes – Cement Bond Logs (CBL), Ultrasonic Cement Logs, Vertical Seismic Profiles (VSP), wellbore gravity measurements and Saturation Logging. In Chapter 5 we look at various methods of monitoring fluids and fluid pressure in the borehole and the formation, including annulus pressure gauges installed at the surface, tubing pressure gauges installed in the subsurface, conventional well tests, and new techniques for direct sampling of fluids from the borehole. In Chapter 6 we look at the latest developments in downhole annulus monitoring technologies, including downhole electromagnetic, temperature, pressure and vibration gauges. We also look at the use of geophones installed in the borehole as 4D seismic receivers or for microseismic monitoring, as an alternative to optical fibers. Finally in Chapter 7 we discuss various other technologies which do not fit in any of the previous categories, but which may have applications in CO_2 monitoring. These include use of downhole tiltmeters, radioactive bullets in the formation to measure displacement and strain, surface-to-borehole controlled source electromagnetic monitoring (CSEM), and self-potential logging.

Based on this review, we conclude that optical fibers and downhole acoustic receivers are the most promising techniques for monitoring CO_2 movement near the wellbore. Optical fibers are a rapidly developing technology that are capable of detecting a range of signals that could be related to near wellbore CO_2 movement, including induced strain, temperature changes, microseismic emissions related to fluid-driven fracture propagation, and changes in elastic properties caused by changes in fluid saturation. They are also relatively cheap and easy to install and can be installed outside the casing in new wells to monitor changes in the formation more easily.

However, downhole acoustic, temperature and pressure sensors can also monitor these signals, so should be considered as an alternative or backup to optical fibers. Recent advances in cementing sensors behind the casing and using either wireless relays inside the casing or the casing itself to transmit signals to the surface, allow sensors to monitor the near-wellbore formation more effectively (although battery life may still be an issue for use in monitoring CO_2 leaks).

Tiltmeters installed in the borehole could provide useful additional information on strain caused by near wellbore fluid movements and should be investigated further. Saturation and gravity logging tools could also help to identify movement of CO_2 near the wellbore, although depth of investigation and resolution may be issues here. Of the other techniques described in this review, Cement Bond Logs and Ultrasonic Cement Logs are mostly useful for monitoring damage to the casing and cement, VSP and surface to borehole CSEM are expensive and have limited resolution and sensitivity to CO_2, pressure gauges and direct fluid sampling are mostly useful for monitoring fluids inside the borehole, radioactive bullets are difficult and expensive to install, and self-potential logging is untested and has poor resolution. We therefore suggest that these techniques should not be considered further for this project.

2 INTRODUCTION

This report summarizes the work done at DTU Offshore as part of the WP1 within the BOMS project to establish an overview of the existing technologies for wellbore monitoring of injected CO_2. Section 3 on fiber optic solutions is partly based on Welltecs report Distributed Fiber Optic Sensing for CCS Wells (see Appendix 1).

The main objectives of the report are to:

- Create an overview of existing technologies for monitoring of a developing CO_2 leak from a storage reservoir to surface via either the near wellbore formation or through external well barriers
- Understand pro's and con's for each method

Note: This report will not include methods for detecting well integrity issues or understanding reservoir injectivity.

Data sources

This report is based on a compilation of data from different types of sources, as well as discussions with several outside vendors and Gas Storage Denmark (hereafter GSD) staff:

1) Previous published state of the art reviews conducted by DTU Offshore (e.g. Bonto et al. 2021, Haines et al. 2023)
2) Publicly available reports from other CCS projects worldwide, whether currently active, decommissioned or never carried out.

3) Published literature.

3 FIBEROPTIC MONITORING METHODS

Monitoring technologies based on fiber optics are developing rapidly. To enable monitoring of the near wellbore formation and the well cement, the fiber will have to be in close contact with the outermost casing. This could be either by installing the fiber on the outside of the casing imbedded in the cement or inside the casing clamped to the casing.

The main advantage of fiber optic monitoring solutions is the continuous data collection enabling trends to be picked up. However, installing fibers in the cement on the outside of the casing can potentially generate a leak path and they can therefore not be installed across well barrier elements.

3.1 DISTRIBUTED TEMPERATURE SENSING - DTS

This type of fiberoptic sensing has been in use since the 1980's and is therefore a very mature solution. For a leakage monitoring application, the DTS does, however, not give enough information on its own. The DTS is very important in combination with DAS to enable interpretation of the recorded data.

3.2 DISTRIBUTED ACOUSTIC SENSING - DAS

Although Distributed Acoustic Sensing (DAS) is less mature than DTS, it is well understood. Research is therefore primarily focusing on improving the signal, image quality and integration with other sensing capabilities (Haines et al. 2023).

Installing permanent DAS systems in both monitoring wells and injection wells can ensure both active and passive monitoring of CO_2 storage including well integrity. Some studies have suggested that DAS would be able to detect noise from CO_2 flow through microannuli around the wellbore, although this is disputed. For example in the reviews of monitoring plans for P18 (Porthos) in the Netherlands on behalf of TNO, one reviewer (NORCE; Gasda et al. 2021) thought that DAS would be able to detect CO_2 flow in this way, while another reviewer (SINTEF; Vrålstad et al. 2021) argued that, given the low flow rates likely from any leak, the noise would likely be masked by the noise of fluid injection (although this might be mitigated by special filtering techniques).

As well as directly monitoring near wellbore CO_2 flow, DAS fibers in boreholes can also have indirect monitoring applications where they are used as low-cost sensors for 4D seismic surveys, microseismic monitoring or chemical detection.

3.2.1 4D seismic using DAS

Research is looking into improving the resolution and repeatability of 4D seismic imaging by placing DAS sensors within the wellbores. These could either complement or completely replace ocean bottom, surface or towed receivers. For example, a pilot study in an onshore hydrocarbon field in Michigan, flooded with CO_2 for Enhanced Oil Recovery (EOR) purposes, used DAS fibres installed outside the casing of two wells as receivers, in combination with an array of vibroseis and dynamite sources, for a 4D VSP study (Grindei et al. 2019, Gupta et al. 2020). A baseline survey was carried out in 2017 prior to CO_2

injection, and then a repeat study was carried out after 16 months of CO_2 injection. It was found that the dynamite sources had a very low signal to noise ratio, so only the vibroseis sources were used in the inversion (Gupta et al. 2020). It was also found that only the DAS cables that were installed in the cement had sufficient acoustic coupling to provide usable data. Despite this it was still possible to image the CO_2 plume.

3.2.2 Microseismicity monitoring using DAS

DAS fibres installed in boreholes can also be used to monitor microseismicity, either to monitor propagation of CO_2 through faults and fractures, or to assess the risk of induced seismicity (e.g. Lellouch et al. 2021). It was recommended as a monitoring technique for the P18 (Porthos) CCS project by both NORCE (Gasda et al. 2021) and SINTEF (Vrålstad et al. 2021).

3.2.3 Chemical sensing using DAS

Research is ongoing to use special coatings on DAS fiber optic cables, which allow them to detect and respond to specific chemicals like CO_2. These coatings work by either changing the optical properties of the fibre, or by inducing a strain in the fibre, that can then be detected in the optical signal returned by the fibre.

Wu et al. (2018) printed μm-scale Fabry-Perot interferometers of poly (1-allyl-3-vinylimidazolium bromide) (PAVB) onto the end face of a multicore optical fiber and showed that this could measure CO_2 concentrations in the range 0-75%. Zhou et al. (2021) used polyether sulfone (PES) to make a low-cost fiber Bragg grating sensor; PES exhibits volume dilation when exposed to CO_2, straining the underlying grating and causing the period and refractive index to change. This was able to measure CO_2 concentrations down to 0.78%, with a 3.27 minute response time.

Metal-organic frameworks (MOFs) are another promising coating material; these can be designed to trap specific gas molecules (e.g. CO_2) in their framework, but to not respond to other gases (e.g. O2, N2 or H2). Trapping CO_2 in the framework causes a change in the refractive index which can be detected by various techniques, e.g. interferometry, evanescent field sensing, transmission spectroscopy or surface plasmon resonance (see Zhu et al. 2021 for a detailed review). Kim et al. (2020) successfully grew CO_2-sensitive MOFs on fiber optic cables and showed that CO_2 exposure (in dry conditions) lead to a drop in transmitted light intensity at 650nm).

However, there is no indication that any of these systems have been tested in the subsurface, either in the wellbore or in the formation, and it is not clear whether they could function under subsurface conditions.

3.3 DISTRIBUTED STRAIN SENSING - DSS

DSS measures strain in wellbore structures to assess mechanical integrity, for more information see Appendix 1.

3.4 DISTRIBUTED PRESSURE SENSING – DPS

DPS provides real-time pressure data for reservoir management, hydraulic fracturing optimization, and well integrity assessment. For more information see Appendix 1.

3.5 DATA MANAGEMENT AND MACHINE LEARNING FOR FIBER OPTIC MONITORING

Continuous borehole monitoring technologies, especially fiber optic cable-based technologies which take readings along the entire borehole, generate huge volumes of data. Moreover, to get the maximum benefit from these technologies, it is necessary to analyse the data in real time to detect leaks or other non-conformance. Much work has recently been undertaken to develop methods of classifying, storing and analysing large data volumes. Data analytics, machine learning, artificial intelligence and digital twins are commonly used approaches.

Mohammadpour and Torabi (2018) present a review of big data applications in the oil and gas and Carbon Capture and Storage (CCS) industries. Big data is characterised by the "5 Vs":

- **Volume:** Seismic surveys and continuous monitoring tools such as microseismic arrays, optical fibers or downhole gauges generate huge volumes of data that must be stored in a way they can easily be accessed.
- **Velocity:** Data is streamed quickly from real-time monitoring tools (e.g. Distributed Acoustic Sensing/Distributed Temperature Sensing (DAS/DTS), seismometers, Logging While Drilling/Measuring While Drilling (LWD/MWD) tools), and it must be processed and interpreted quickly to get the maximum value (for example to manage drilling operations, or to take preventative action to mitigate leaks).
- **Variety:** Data is acquired in many different formats, some of which are structured (e.g. databases) and some unstructured (e.g. text-based).
- **Veracity:** Data is often noisy and must be filtered or processed to remove invalid data and extract the signal.
- **Value:** With correct handling, big data can give operators a commercial advantage; however, with poor handling that advantage is lost. Examples include:
    - Automated seismic interpretation by Machine Learning.
    - Using microseismic data to map hydraulic fracture propagation.
    - Using LWD and MWD data to manage drilling operations – improving efficiency and minimising the risk of blow-out or well failure.
    - Real time updating of reservoir simulation models using DAS or DTS data – especially in fractured reservoirs or reservoirs with Enhanced Oil Recovery (EOR).
    - Optimising well performance.
    - Optimising hydraulic frac jobs.
    - Monitoring CO_2 leakage.

Various tools are available for handling big data. For data management, examples include Hadoop (from Apache), MangoDB and Cassandra, while for data analysis, tools include R, Datameer and Bigsheets (from IBM).

Examples of actual applications include:

- Barros and Boullenger (2020), who used a neural network to classify 4D seismic and downhole pressure datasets from the Smeaheia CCS project in Norway as either conforming or non-conforming scenarios, where non-conformance was defined as CO_2 leakage from the main trap within 150 years of the end of injection. The training dataset consisted of simulations of Smeaheia using multiple input cases representing the range of uncertainty in key parameters, and synthetic output datasets generated from these simulations. Thus trained, the neural networks were able to accurately differentiate conformance and non-conformance cases from present day data, taking into account noise, sparse measurements and the requirement for forward prediction.
- Wang et al. (2020) present a study comparing the ability of various different machine learning algorithms to predict CO_2 saturation from time-lapse 2D seismic surveys, downhole pressure and Total Dissolved Solids (TDS) data. The training datasets are again taken from simulations and synthetic datasets, based on a real CCS prospect at Kimberlina, California. They show that training the algorithms on 2D seismic data alone gives better accuracy than training them on downhole data (pressure and TDS) alone, but that combining both gives the best results. At shallow and intermediate depths the Recurrent Neural Network (RNN) algorithm gives better results, but at greater depths the linear Support Vector Machine (SVM) algorithm gives the best results, when the full dataset is used.
- Shaheen et al. (2021) use a convolutional neural network (CNN) to distinguish low magnitude earthquakes from noise in real-time microseismic data from the Groningen gas field, onshore Netherlands. This gave significantly better results than the conventional method (comparing the ratio of short-term amplitude to long term amplitude).
- Bello et al. (2017) present a new tool for Downhole Big Data Management, for managing and real-time interpretation of downhole data including DAS/DTS data. They also give a number of case studies of applications, including use for monitoring caprock integrity in a steam injection oilfield, using fiber Bragg grating sensors. This gives real-time warnings if the caprock is at risk of mechanical failure due to induced strain.

4 DOWNHOLE LOGGING TOOLS

Within the oil and gas industry downhole logging is a standard method for getting information about the formation fluid, permeability, cement quality etc. It is therefore natural to consider how downhole logging can be included in a CO_2 monitoring programme. The logging can be split into cased hole logging and open hole logging.

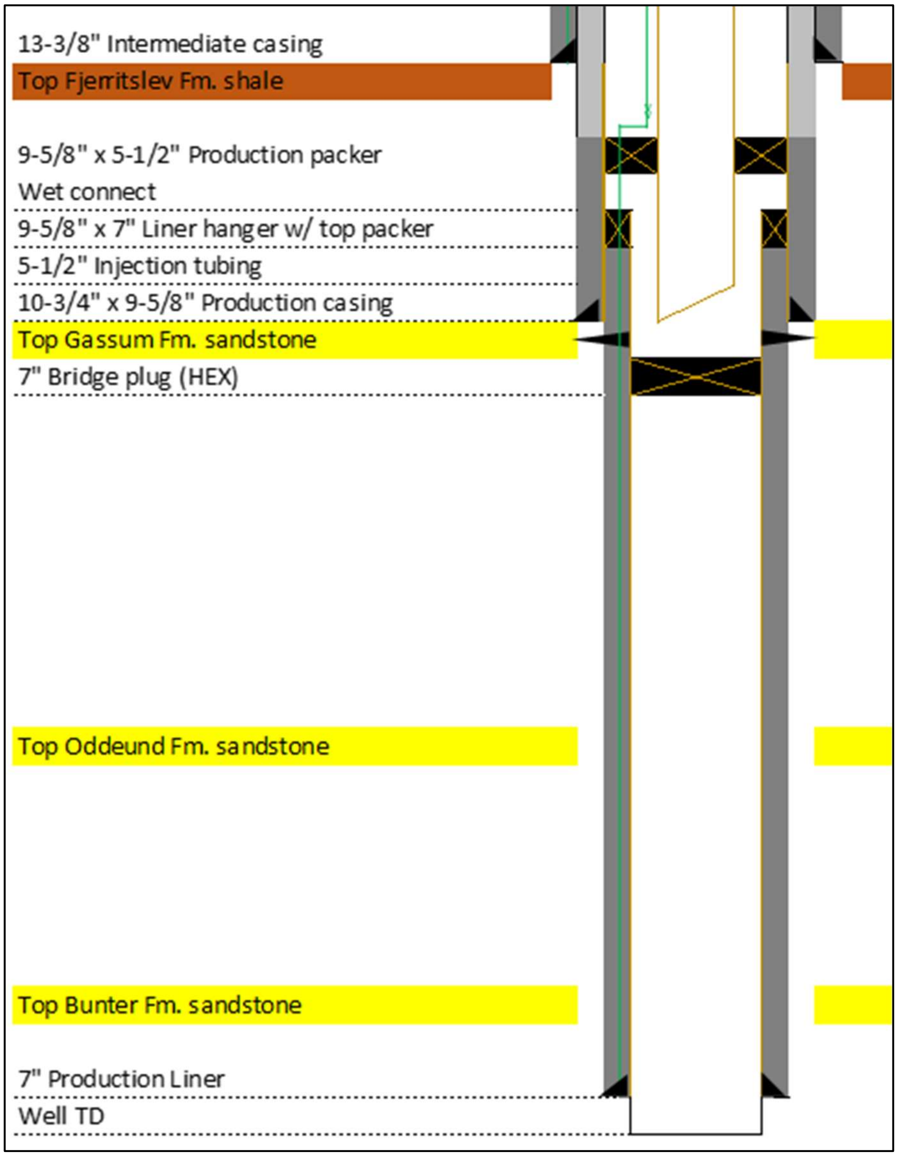

Figure 4.1: Schematic well drawing for GSD well

4.1 CASED HOLE LOGGING

Cased hole logging is performed through already installed casing strings which gives some limitations. Figure 4.1 is a schematic well drawing of a typical Gas Storage Denmark well in Stenlille. In such a well logging can be performed in the production tubing, however, to be able to provide reliable data about the near wellbore formation or the well – cement interphase, most logging tools require contact with the outmost casing.

Logging tools can also be run through the tubing tail pipe and into production liner. Pending the well deviation and the logging tool design this might increase the risk of the logging job as the tool might hang up on the way back into the tail pipe.

Tools performing logging through two casing strings are being developed, however, they are not currently ready for the marked. If the development of these tools is successful it will mean that the logging can be performed more frequently in the wells (injection or monitoring wells) as a workover is not required. The data points will, however, still be with a large time step between them and looking for developing trends will therefore be a challenge.

4.1.1 Cement bond logging

A standard CBL log is an acoustic log which provides indirect information about the coupling of the cement to the casing and the formation. The logging tool consist of pulsing transmitters and a number of receivers measuring the amplitude of the waves propagating axially along the casing. The measured response depends on the fluid inside the casing and the cement/fluid in the annulus and therefore these parameters must be known to interpret the data.

This type of logging tools can’t detect channelling in the cement but can clearly indicate the top of the cement. Channelling in the cement can be detected by running the CBL in combination with ultrasonic logging tools. The CBL logging tool can be run in combination with a VDL log (variable density log) to improve the understanding of the response in wells with ‘hard formations’.

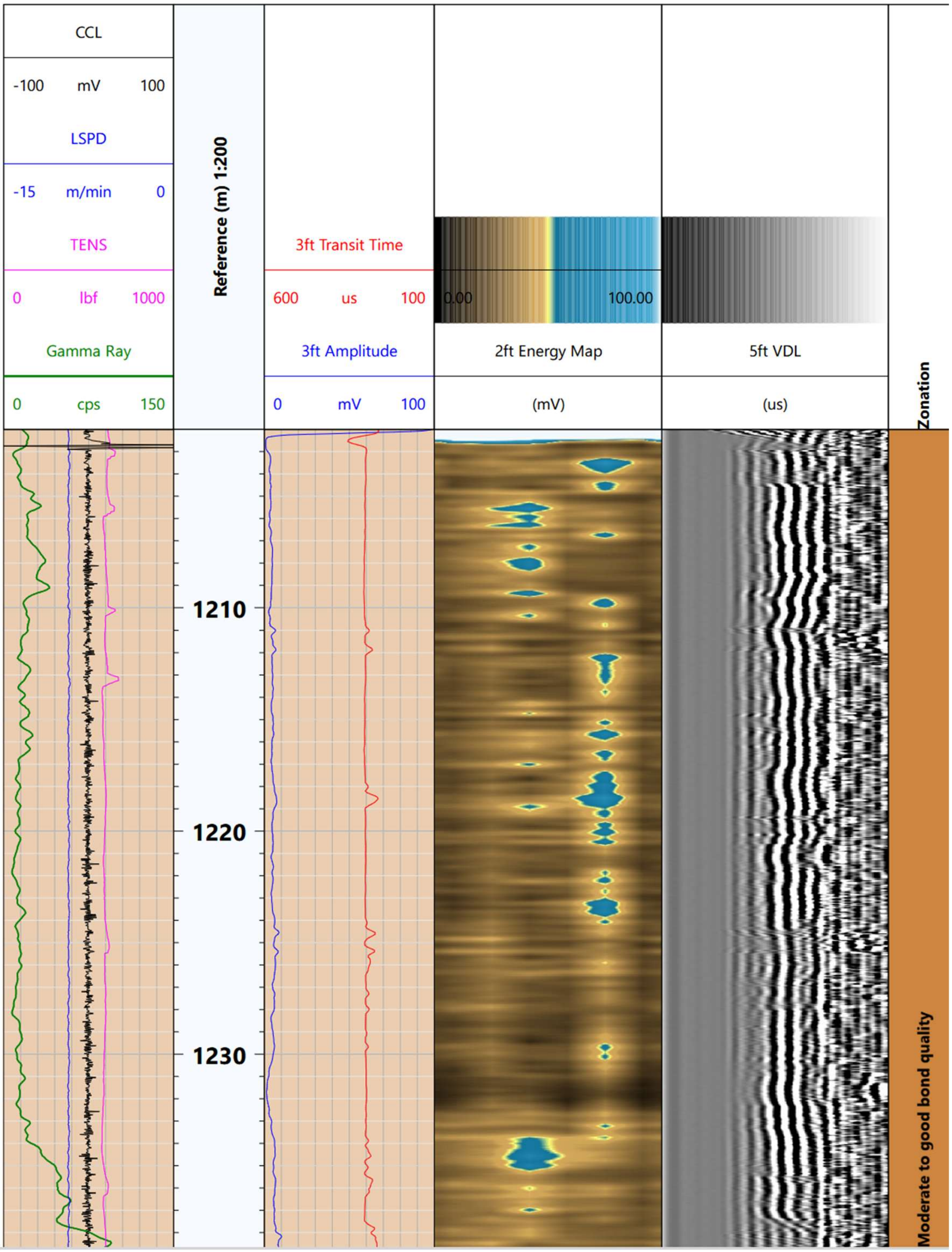

Figure 4.1: Cement bond log from ST-06, 2021

4.1.2 Ultrasonic cement logging

If the CBL/VDL logging tools are combined with an ultrasonic log it can identify micro annuli in the cement. The Ultrasonic tool can provide acoustic impedance of the material beyond the casing, it is however, very sensitive to the fluids within the well. This combination of logging tools will give a very good 360 deg indication of the quality of the bond between the casing and the cement, and cement channelling, it is however, a stretch to say something about the formation based on the response.

4.1.3 Vertical Seismic Profile – VSP

The VSP logging is a downhole seismic logging which can be used as a correlation of the surface seismic. VSP logging can be performed in both open hole and cased hole, the latter is often preferred to avoid wellbore stability issues.

The wellbore image is obtained by placing geophones against the wellbore.

4.1.4 Saturation logging

The reservoir saturation log is a pulsed neutron generator and a detector spectrometry system which will measure the element concentration in the formation. This type of logging is often called C O logging as it measures the Carbon and the Oxygen atom concentration in the formation fluid. The concentrations are then used to understand the proportion of respectively water and hydrocarbons in the reservoir.

As the saturation logging measures Carbon and Oxygen it can also detect CO_2 (Kennedy et al. 2019). It will however be interesting to investigate if the tool can distinguish between hydrocarbons and CO_2.

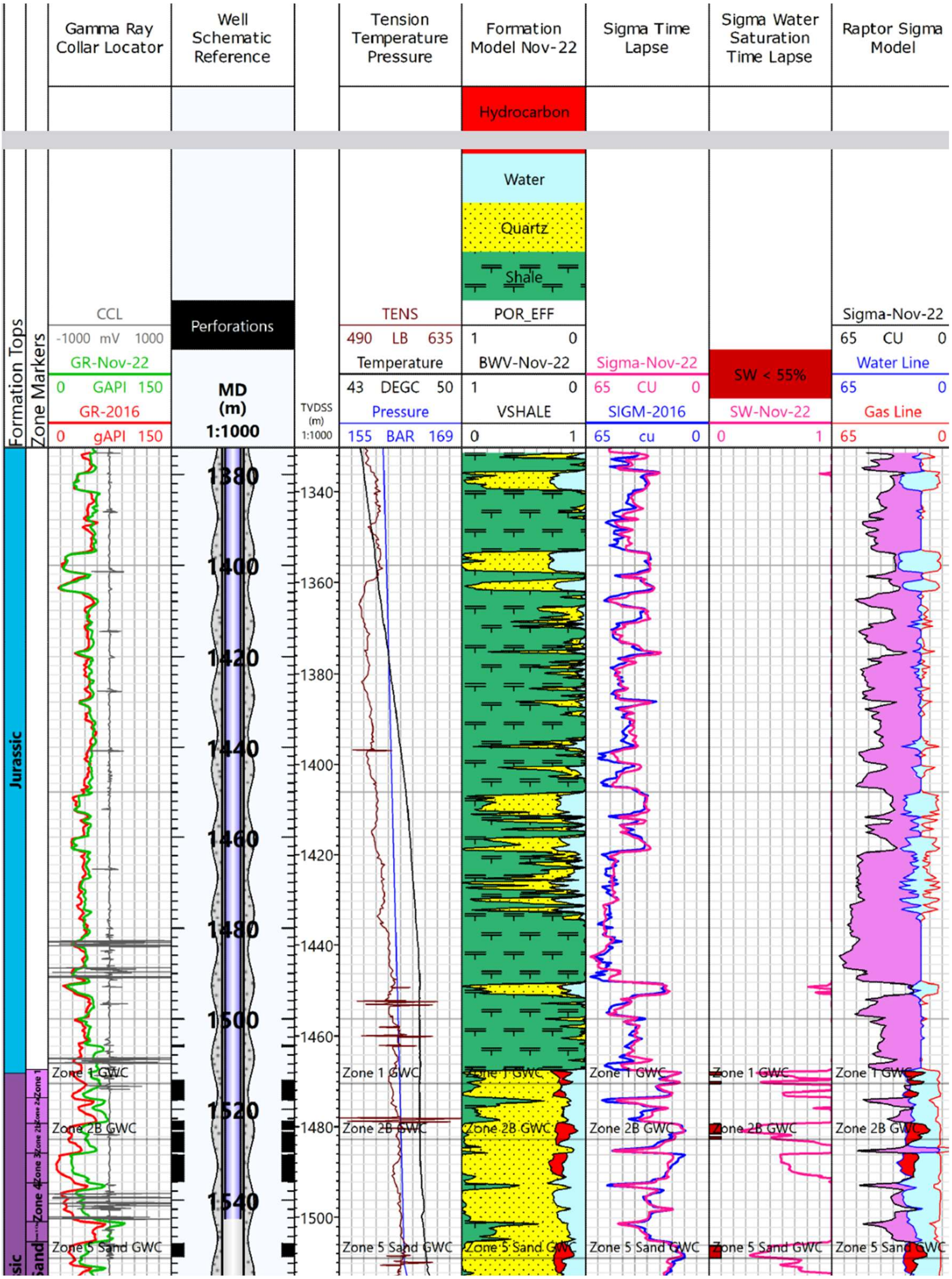

Figure 4.2: Gas saturation log from ST-02, 2022

4.1.5 Wellbore Gravity Measurements

Using gravity tools in the wellbore allows a much more accurate detection of density changes in the near wellbore environment than gravity measurements made at the surface (Winthaegen et al. 2005). Downhole gravity tools have been used since the 1990s to identify the location of fluid contacts from the density contrast between different fluid phases (e.g. Brady et al. 1993).

Three-axis gravity meters can be fitted into a 54-mm diameter wireline tool and run in cased boreholes. They have improved in accuracy in recent years and are now able to measure gravity boreholes to a precision of 5μGal, independently on three orthogonal axes. When used to calibrate detailed flow models, this technique can be used to monitor flood fronts with high precision (Lofts et al. 2016). They have a much greater depth of investigation than traditional cased hole tools (e.g. density tools), so can be used in time-lapse studies to measure changes in regional fluid contacts, away from the effects of coning around the wellbore.

4.2 OPENHOLE LOGGING

Openhole logging is used to acquire information about the formation, fluids etc. prior to installation of the casing. This means that in terms of monitoring of injected CO_2 it is not very useful as information can only be obtained at the drilling point in time and for that reason, openhole logging has not been included in this report.

In a monitoring well, it could however, be considered to install a glass fiber casing across the section of interest if magnetic logging tools are to be used.

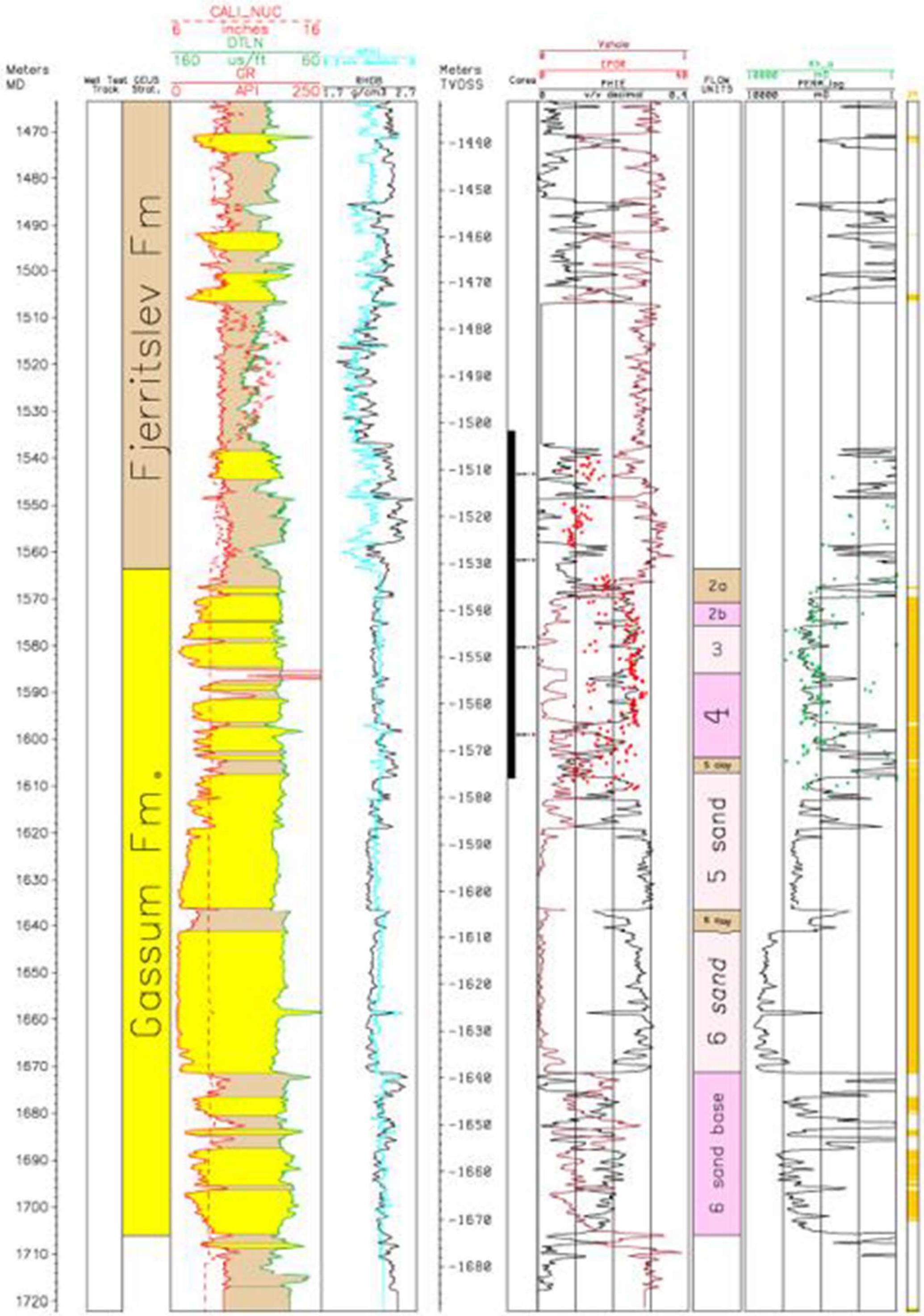

Figure 4.3: Open hole log, ST-06

5 PRESSURE AND FLUID MONITORING

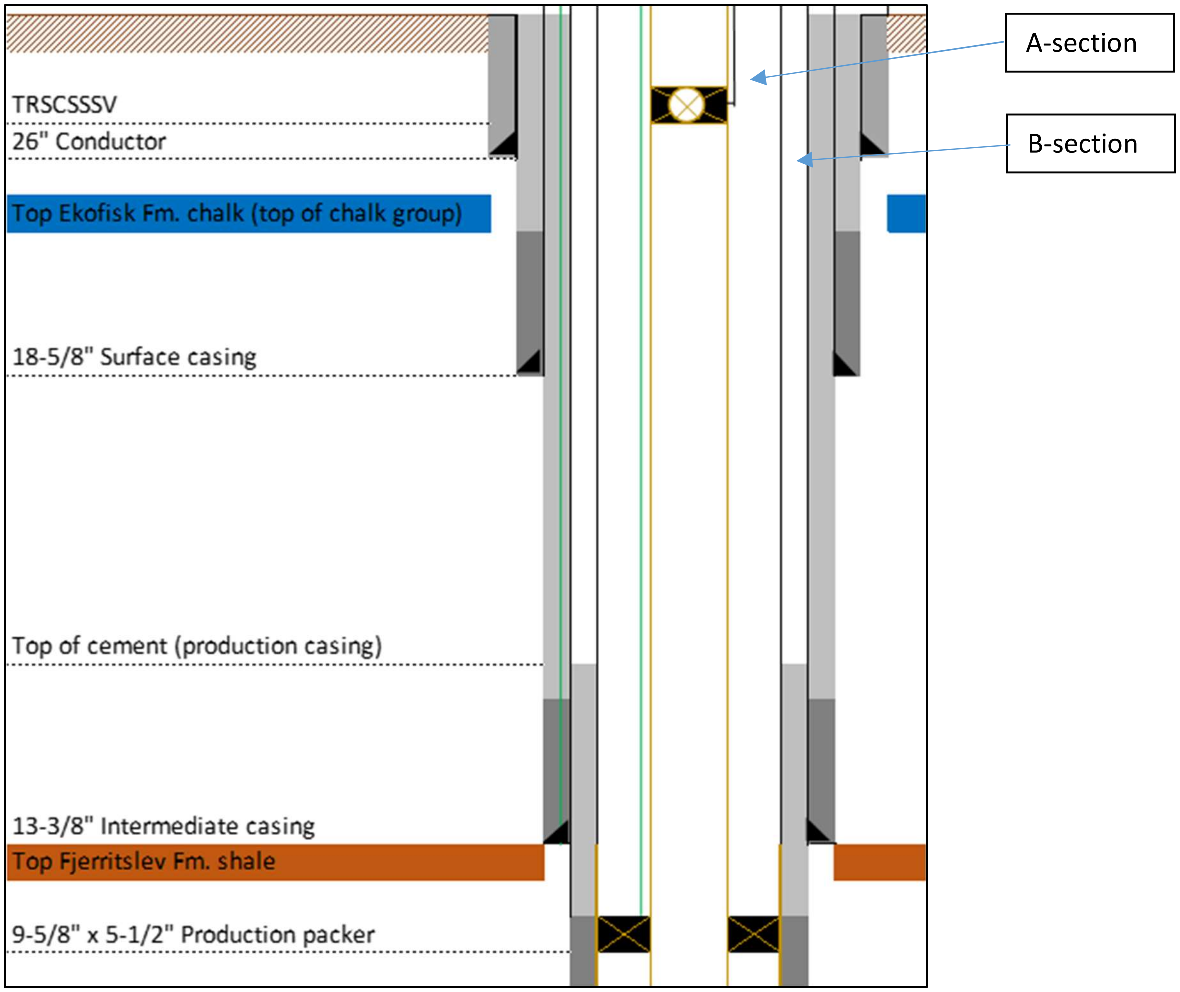

Figure 5.1 Well schematic with A-annulus marked

5.1 SURFACE INSTALLED ANNULUS GAUGES

Annulus gauges is the simplest and most cost-effective form of monitoring of changes of pressure in the formation with which the annulus is in communication. In addition, the annulus gauges are key for monitoring of well integrity. However, in most cases the annulus is cemented into the previous casing and therefore a change in pressure is only seen if the cement is of suboptimal quality. Figure 5.1 is a typical well schematic with identification of the A-annulus, subsequent annuli are named B, C etc. As an example if the pressure change in the shale section has to be monitored, a gauge should be installed on the B-annulus.

For CO_2 injection wells it is key to have annulus pressure gauges installed to monitor well integrity and the quality of the well barriers. However, these gauges cannot be relied on to monitor CO_2 leakage due to a breach of the caprock which is not caused by well barrier failure. If a dedicated observation well is drilled and designed for monitoring of the cap rock integrity, annulus gauges can be used to monitor CO_2 progression.

5.2 SUBSURFACE INSTALLED TUBING GAUGES

Downhole installed tubing gauges in a monitoring well can be used to monitor for pressure increase and thereby give information about the horizontal travel of the CO_2 towards the well. Downhole pressure gauges can be continually monitored from a control centre (e.g. Hansen et al. 2013), or they can store the information in memory for later retrieval and analysis (IEAGHG 2020); see Section 6 for more details. They are particularly useful for monitoring well tests (see Section 5.3). To get the best results however it is essential to place the gauges in the reservoir. In the case of the Snøhvit CCS prospect, the gauges were installed c.800m above the reservoir due to operational issues; as a result it was not possible to conduct transient analysis of well test data due to temperature and phase effects, although reservoir pressure could still be calculated (Hansen et al. 2013).

Injection Logging Tools (ILTs) are equivalent to Production Logging Tools (PLTs) but measure rates of fluid flow into the reservoir rather than out of it. They can be used to differentiate injectivity in different sections of the reservoir and identify the intervals of high inflow. Although they often give no better stratigraphic resolution than 4D seismic data (Hansen et al. 2013), they are much cheaper to run.

5.3 WELL TESTS

Well tests cannot directly monitor movement of the CO_2 plume, but history matching of well test data is useful to constrain injectivity and compartmentalisation of the reservoir and to calibrate the subsurface flow models, which can then better predict the movement of CO_2 in the subsurface (e.g. Hansen et al. 2013, Shi et al. 2013). Short shut-ins (lasting a few minutes) are useful to constrain skin effects and to establish local pressure without temperature effects, while longer shut-ins (several months) can help to constrain compartmentalisation of the reservoir. For example, long shut-ins of the Snøhvit CO_2 facility due to problems at the CO_2 processing plant, were used by Shi et al. (2013) to establish fault compartmentalisation of the injection reservoir.

5.4 DOWNHOLE FLUID SAMPLING

Direct sampling of formation fluids can be helpful in monitoring conditions in the reservoir, but it is generally expensive (>10k USD per sample) and difficult to achieve without contamination, especially during injection or in a multiphase environment. However, Freifeld (2009) describes an experimental system designed to allow continual sampling of fluid from an injector well, which was tested in the Frio Brine Pilot project, Texas. This system consists of a U-tube extending from the surface to the reservoir, with a valve at the base. When the reservoir is sealed off by a packer and the valve is opened, formation fluid fills both branches of the U-tube to the hydrostatic level of the fluid. If the valve is then closed so the U-tube is sealed from the wellbore, inert gas (N_2) can be pumped into one branch of the U-tube to displace fluid from the other branch, as shown in Figure 5.2. This can allow 20-30 litres of formation fluid to be collected before the system is flushed and the valve reopened to repeat the cycle.

In the pilot test, real time fluid analysis was carried out at the surface to determine pH, alkalinity and gas composition (using a mass spectrometer). Samples were then taken to the lab for further analysis. This could include microbial analysis, or isotopic analysis (although exposure to surface pressure is a threat to reservoir microbial life, so for microbial analysis, sample preservation at reservoir pressure is recommended). The isotopic composition could be compared with CO_2 samples collected from higher levels, to differentiate naturally occurring CO_2 from CO_2 leaking from the reservoir (McNeill et al. 2014).

The system has subsequently been applied to the active Otway CCS project in Australia. It is capable of providing continual fluid monitoring over several years.

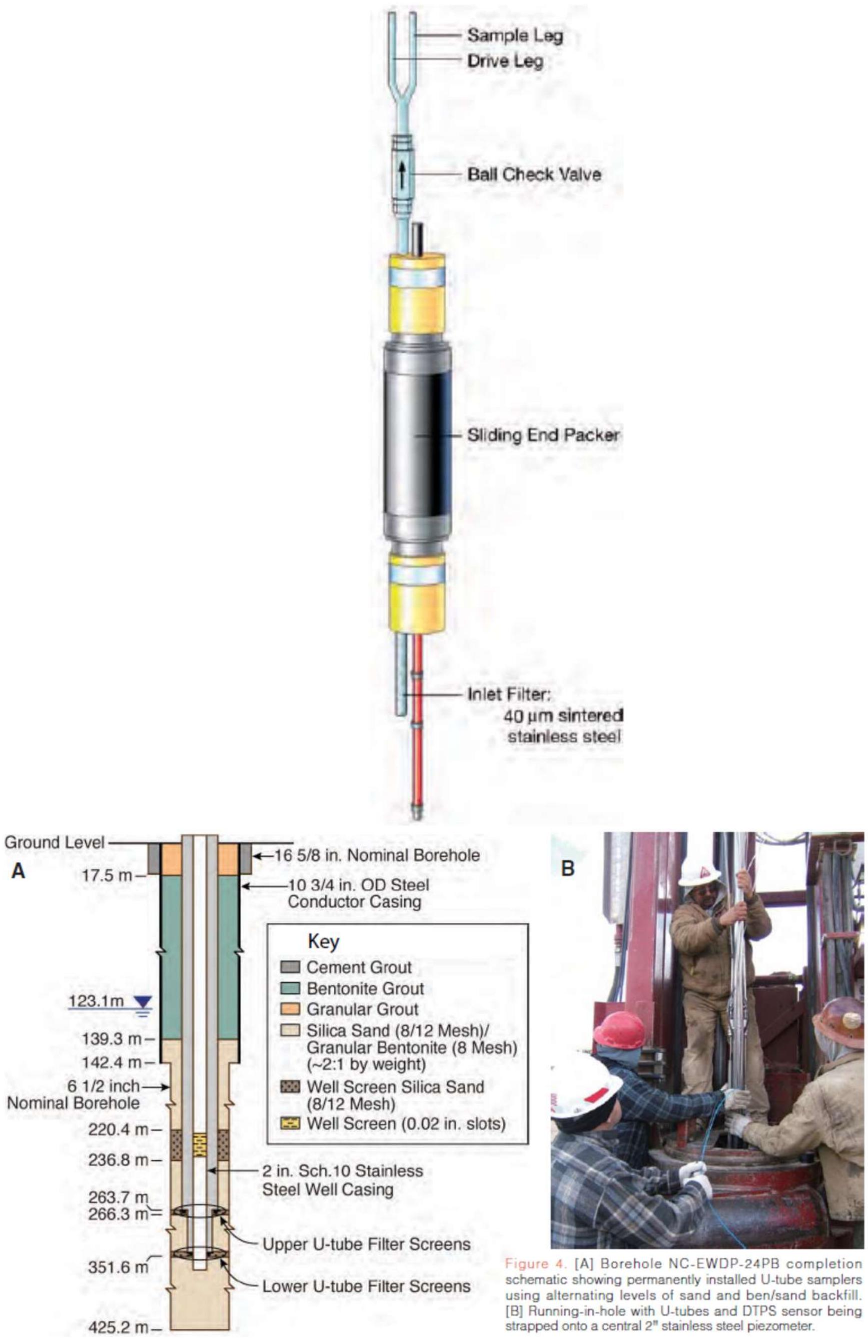

Figure 5.2: Schematic layout of the U-tube sampling system deployed at the Frio site, Dayton, Texas (left), Borehole NC-EWDP-24PB completion schematic showing permanently installed U-tube samplers using alternating levels of sand and ben/sand backfill (centre), and Running in-hole with U-tubes and DTPS sensor being strapped onto a central 2” stainless steel piezometer (right). All diagrams from Freifeld 2009.

6 DOWNHOLE ANNULUS MONITORING

6.1 CATS EMX PRESSURE AND TEMPERATURE GAUGES

CaTS EMX (Cableless Telemetry System Electro-Magnetic Sensor) is a long-term pressure and temperature monitoring system which can be placed behind the casing in the cement (clamped onto the casing). It can also be retrofitted into old wells on wireline. The CaTS gauges can be installed either together with a perforation system (timer activated) to get access to the formation through the cement or on their own.

The communication to the gauges is electromagnetic pulses via the casing string which means that the gauge is not connected to a cable or similar. The battery life of the gauges is up to 10 years, but will depend on the resolution of the data and the collection frequency. The data frequence and accuracy can be adjusted from surface and the gauge store the remaining data which can be retrieved at a later point if required. The system will need a repeater every 3-400 m but apart from that there is no limitation with respect to depth, well pressure, temperature and inclination.

The CaTS EMX gauges have a track record for being used by the offshore industry.

The advantage of the CaTS EMX system over the fiber optic system is that the gauges can be placed below a well barrier element without hampering the quality of the remaining part of the cement job as it has no cable or fiber connection to surface. In addition, this type of pressure gauge is significantly cheaper than a fiber optic solution. The CaTS system can include several gauges on the same casing and up to 20 gauges have been deployed on the same string.

A gap is to understand the battery lifetime based on the accuracy of data required to pick up a developing CO_2 leak.

6.2 REVEAL MONITORING SYSTEM

The reveal system is a high-speed distributed downhole sensor array which communicates to surface via a cable. The system monitors pressure, temperature and tri-axial vibrations.

The Reveal system can be placed in the annulus and also in the cement, however, due to the cable it will, like fiber optics, be a risk for generation of a potential leak path. Therefore, the reveal system can only be installed above the well barriers.

Reveal is a system which is under development but close to marked implementation.

6.3 GEOPHONES

Geophone arrays can also be emplaced in boreholes. These can be used either for 4D seismic surveys or for microseismic monitoring, instead of DAS cables.

The advantages of using borehole receivers for 4D seismic survey are improved coverage and repeatability (their position will be the same for repeat surveys). The same advantages apply for microseismic monitoring. These advantages are also common to DAS cables, and are discussed in more detail in Sections 3.2 and 6. However, we will note here a microseismic monitoring study of the Tomakomai CCS pilot project in Japan, which used conventional downhole seismic receivers in 3 monitor wells to detect microseismic events down to magnitude -0.5. This detected 9 events prior to injection and 3 events after injection, all of which were in basement at >6km depth (the CO_2 itself was injected into two reservoirs at 1.0-1.2 and at 2.4-3.0km depth). A large (magnitude 6.7) earthquake struck 30km away from the injection site during operations, although injection had been temporarily shut-in for operational reasons a few days beforehand. However, there was no evidence of local seismicity or leakage of CO_2 in the site as a result of this (Tanase et al. 2021).

7 OTHER DOWNHOLE MONITORING METHODS

7.1 TILTMETERS

Tiltmeters measure inclination to micro-radian accuracy. They are often used at the surface or seabed to monitor subsidence or uplift, but can also be fitted into wellbores to measure changes in wellbore inclination. Since change in inclination of an initially vertical marker is a gradient of the applied strain, integrating the tiltmeter measurements can be used to calculate strain around the wellbore.

Warpinski et al. (1997) show that tiltmeters can be sufficiently sensitive to measure strain induced by opening and propagation of fractures near the wellbore. For simple dynamic fractures (e.g. circular or linear fractures held open by fluid pressure), linear elastic fracture mechanics can be used to calculate the strain induced by fracture opening. For more complex fractures, e.g. fractures held open by proppant or surface asperities, the strain field can be calculated numerically using finite element models. The tiltmeter data can thus be inverted to determine the location, height and aperture of the fracture even if it does not intersect the wellbore.

Warpinski et al. tested this at a site the Piceance Basin, Colorado, using a linear array of 6 biaxial tiltmeters cemented into an observation well, located c.100m from a well which was hydraulically fracced. Microseismic monitoring was also carried out to map the growth of the hydraulic fracture. They showed that the tiltmeter data was able to accurately track the growth of the propagating fracture, and estimate its height and aperture. Even after fraccing, when the frac fluid had dissipated, the tiltmeters showed a residual tilt, which could be used to calculate the residual fracture aperture due to propping. Furthermore, this technique can be used to monitor fracture opening and closure during well tests, and thus determine fracture opening and closure pressure. This does require accurate measurements of the elastic moduli (within 10%); however, Warpinski et al. found that static measurements based on geomechanical tests of core samples were sufficient for this purpose.

7.2 RADIOACTIVE BULLETS

The technique of using radioactive bullets as location markers to measure strain in the formation was developed in the 1970s in Alaska, to measure deformation due to thawing of the permafrost around the wellbore. It was generally applied in conjunction with various techniques to track the casing collars and thus measure strain in the casing. Ruedrich et al. (1978) describe a study where bullets were fired into the formation at 20ft intervals, and could then be tracked using repeat gamma ray logs with c.10cm positional accuracy. This was sufficient to show extensional strain below the thaw zone and in the sand layers, and compressional strain immediately above the thaw zone and in the shale layers. They also showed that strain in the casing approximately matched strain in the formation.

Allen (1984) used the same technique that was applied to measure production-induced compaction in a well in Wilmington, California. To detect production-induced strain, a higher spatial resolution (<1cm) is required. One problem is that “bounce” of the gamma ray tool used to detect the bullets (i.e. stretching of the tool string as it is raised through the wellbore) can lead to greater positional inaccuracies. To counter this, Allen developed a tool string with two odometer wheels attached, to measure movement of the tool string itself with high accuracy and correct the position of the bullets. They also used a system with two sensors on the tools string, placed approximately the same distance apart as the bullets (or casing collars for the collar detectors). This allows more accurate determination of the relative position of adjacent markers. By these means they were able to obtain accuracy of <1cm in the location of the casing collars, although the best accuracy they could obtain for the bullet locations was c.3cm at normal logging speeds (accuracy could be improved slightly by reducing the logging speed, but this led to recording issues).

More recently, the technique has been used to measure subsidence due to pressure depletion in HPHT fields in the North Sea. Banks et al. (2021) describe a study by Total in the Culzean field in the UK sector. Bullets were emplaced at 10m separation, and relative position was measured using dual gamma ray detectors spaced the same distance. After an initial calibration survey, further measurements were taken annually. Six repeat tool runs were used for each measurement, which enabled the bullet to be located with an accuracy of <2mm. However, the challenging HPHT environment led to many problems; extensive testing of the bullet firing system was required to ensure bullets would not become broken (leaking radioactive material) or drop into the wellbore, and the project was carried out in close collaboration with the regulators. One major issue was that it was not possible to fire bullets into the reservoir itself, since there was a risk of damaging the bullets during perforation. Therefore 4 to 5 bullets were fired into a shale unit separating two of the reservoirs. It was not possible to directly measure compaction of the reservoir, but instead strain in this shale unit was used to calibrate the geomechanical models which were then used to predict compaction in the reservoir itself.

By contrast Zhou et al. (2023) carried out a similar study on an HPHT field with a sandstone reservoir in the Norwegian sector for Equinor, and were able to fire bullets into the reservoir itself. They used an off-the-shelf Baker CMI tool system that emplaces bullets at varying intervals between 3 and 30m. Bullet positions were remeasured at 1, 7 and 16 years after the initial calibration survey. Results were again used to calibrate the geomechanical models of the field, in conjunction with platform GPS and caliper logs measuring casing deformation. The results after 7 years gave a good match for the model assuming only elastic compaction, with the exception of two bullets, one of which was assumed to be dislodged by perforation. However, the bullet locations after 16 years showed that measured subsidence was greater than that predicted by the model, probably because the simulation did not include creep.

7.3 SURFACE TO BOREHOLE CSEM

Controlled-source electromagnetics (CSEM) is a subsurface imaging technique that is sometimes used as an alternative to 3D or 4D seismic data. CSEM responds to variations in the resistivity in the subsurface; however the use of CSEM to monitor CO_2 plumes may be difficult due to the low resistivity contrast between CO_2-saturation reservoir and water-saturated reservoir (Park et al. 2013).

CSEM was tested as a tool for monitoring the movement of the CO_2 plume in the Sleipner project, Norway; however the resistivity contrast of c.5% between the CO_2 plume and the surrounding aquifer is near the limit of detection of surface-based CSEM (Park et al. 2013). Furthermore, there was no baseline survey prior to CO_2 injection. To get around these problems, a surface to borehole CSEM network was used. This gives a higher resolution, although even this was not able to differentiate between CO_2 in 9 separate thin reservoirs separated by shales (as was the actual case) and a CO_2 in a single 180m thick anisotropic reservoir (as was used for modelling) (Park et al. 2013).

7.4 SELF-POTENTIAL

Self-potential (or spontaneous potential) has also been suggested as a method of monitoring the movement of a CO_2 front in the subsurface (Winthaegen et al. 2005). A mobile CO_2 plume may induce self-potential by two mechanisms: electrokinetic coupling, due to the interaction of CO_2 and the electrical double-layer on the walls of the pores, or by the geobattery effect whereby the metallic well casing acts as a vertical electronic conductor connecting regions of differing redox potential (Ishido et al. 2013, Nishi and Ishido 2022). The former mechanism can be detected by surface sensors, while the latter mechanism can be detected using electrodes connected to the wellhead pipe and should be able to detect the CO_2 front approaching the borehole. When this was tested in a well at the Farnsworth Unit in Texas, no signal was found, although it is not clear if this was because the CO_2 front did not approach the well or because the signal was below the detection resolution (Nishi & Ishido 2022).

8 DISCUSSION

Depending on the objective of a CO_2 monitoring program there are a number of solutions to choose from. However, when specifically monitoring for vertical movement of the CO_2 past the well barriers and caprock there are fewer technologies.

8.1 DETECTION OF CO_2 BREACHING THE WELL BARRIER/CAPROCK

There is a limited number of solutions to detect this breach before the CO_2 has passed the well barrier as cables and fibers can't be placed within the well barrier. In this report only the CaTS EMX gauges have been listed. These gauges can be placed in the well barrier cement and detect pressure changes in the cement.

8.2 DETECTION OF CO_2 HAVING PASSED THE CAPROCK/WELL BARRIERS

Monitoring above the well barriers opens up for a number of monitoring solutions as cables and fibers can be installed. These solutions include fiberoptic solutions like DAS/DSS/DPS and the Reveal monitoring system.

8.3 MONITORING IN CONNECTION WITH WORKOVERS

In connection with workovers cased hole logging can be performed to understand the vertical movement of the CO_2. Especially the saturation logging could potentially be interesting to look at. This type of monitoring will, however, only be at one point in time.

8.4 MONITORING WELLS

In monitoring wells it could be interesting to look at installation of tiltmeters to potentially detect any developing fractures.

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APPENDIX 1

Fabio Rosas, Welltec, Distributed Fiber Optic Sensing for CCS Wells