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MPH

BOREHOLE MONITORING SOLUTIONS (BOMS)

1. Introduction

The BOrehole Monitoring Solutions (BOMS) project is part of the INNO-CCUS partnership that was founded in 2021. The project aims to investigate and develop methods for monitoring CO_2-wells to ensure sound and safe operations of CO_2-storage sites. The project is driven by a collaboration of five partners from industry and academia:

- **The Technical University of Denmark (DTU)** is driving the main part of the research in the project, namely investigations on how changes in the signal from optical fibers can be used to interpret changes in the mechanical properties of the near wellbore rocks and cement.
- **The Geological Surveys of Denmark and Greenland (GEUS)** investigates how reservoir simulations can be improved by using data from the wells.
- **Technion – Israel Institute of Technology** provides expertise in optical fiber solutions for monitoring.
- **BlueNord** is a cofounding industry partner with expertise in offshore oil and gas operations.
- **Welltec** is a producer of tools and well completion equipment and provides expertise in integrating monitoring equipment in the wells.
- **Gas Storage Denmark (GSD)** is an operator of two natural gas storage sites and is developing a CO_2-storage site that will be used as a case in the project.
- In addition, **Wellperform** has been contracted by GSD to perform the well design.

For geological storage of CO_2 to be an acceptable method for climate action, it is necessary to demonstrate a very high level of security for the CO_2 to be completely and permanently contained in the underground reservoir. One of the largest risks of leakage is through the wells or along the wellbore; i.e. those points where the otherwise sealing cap rock has been penetrated in order to access the reservoir. To ensure that the wells do not cause any leakages from the reservoir, and to make mitigation actions possible, should a leakage occur, a comprehensive monitoring program for the wells is necessary. In the oil and gas industry, this has been done for many years, and likewise in existing CO_2-storage projects worldwide. However, there are still limitations to sampling frequency, monitoring parameters, and regions of interest for monitoring, and therefore more research and development on the subject is key to safe CO_2 storage and consequently public acceptance. The BOMS project addresses this by investigating the operational needs for monitoring, establishing an overview of existing technology and by improving the ways wells and near wellbore region of the reservoir can be monitored. The project will have a particular focus on the use of optical fibers for distributed sensing of various parameters, since this is a technology that has proved efficient for downhole monitoring and has many more promising applications. These downhole monitoring technologies are at the start of the project at a TRL5 and the aim is to mature them to TRL7 through the cause of the project.

1.1 Application

The BOMS project is considering monitoring solutions in general terms with the goal that the results can be applied by operators on a wide range of CO_2-storage projects. However, it is often more convenient to explore complex systems by choosing a relevant case to limit the number of variables. As an example, it is necessary to choose some specific reservoir samples for the experiments to be performed in the project.
GSD is currently working on establishing a CO_2-storage site in Stenlille, Zeeland, Denmark, in the proximity of a nearby gas storage facility, of which GSD is the operator. As a

partner in the BOMS project, GSD can provide reservoir data and samples and detailed well designs of interest for the BOMS project, and the location of Stenlille close to the offices of the project partners makes Stenlille a suitable choice for a case. The BOMS project aims on generalizing the results and discussions based on the Stenlille case to make the results applicable by as many operators as possible.

1.2 Well terminology

Since the BOMS project is considering methods for downhole monitoring, discussions and descriptions of the wells and equipment for those plays is a central role in the project. In this section, we therefore describe some of the most important terminology and concepts necessary to understand the work and findings of the project.

The most basic part of a well is the *borehole*, which is merely a hole drilled into the underground (see Figure 1.1).
For CO_2 storage projects, the well should be at least about 800 meters deep, since at this depth the temperature and pressure are such that the CO_2 will be in supercritical phase, where the density is much higher than at surface conditions, and hence the underground volume that the CO_2 occupies will be much smaller, by a factor of up to 400.
The diameter of the hole will have different sizes with depth pending the expected vertical pore pressure distribution, and typical diameters are some few tens of inches.
In each borehole section, a steel pipe called a *casing* is inserted and cemented in place to isolate weaker formations before subsequent section with higher pressure is penetrated. The thickness of the steel is usually about ½ inch, depending on the conditions in the specific well. In the cavity between the geological formations and the casing, *cement* has been pumped from the bottom of the well and upwards to ensure that no gases or fluids can migrate upwards along the well. The cementing can be done partly or all the way to surface again pending specific conditions. The combined effect of the cement and the casing acts as a barrier between formation fluids and the surface or between the formation fluids and shallower layer with e.g. drinking water. At the same time the casing/cement stabilizes the borehole so that fragile layers in the underground will not collapse into the hole.
Inside the casings, another steel pipe is installed, called the *tubing*, where the fluid of interest (e.g. CO_2) will flow into the well. The tubing will, together with other safety equipment, acts as a primary *barrier* containing the fluid, while the casing and cement act as a *secondary barrier*. The cavity between the tubing and the casing is called the *annulus*.
All Danish wells should comply with this two-barrier principle.
In a completed well, there may be many annuli. The 'A' annulus is the void between the production tubing and the smallest casing string. The A annulus can serve a number of crucial tasks, including monitoring of integrity and gas lift purpose. A normal well will also have a 'B' and frequently a 'C' annulus, between the different casing strings. These annuli will not have any connection to well bore fluids unless a barrier has failed and therefore monitoring of annulus pressures is important to ensure integrity of the barriers (see Figure 1.1).
Access to the reservoir is typically achieved by shooting holes (*perforations*) in the casing below the end of the tubing or by installing tubing with screens or holes across the reservoir interval if a casing is not run into the reservoir. To preserve the two-barrier principle, a *production packer* is installed to provide a seal between the outside of tubing and inside of the casing to ensure reservoir fluids do not enter the annuli between the two.
On the surface, the tubing and the casing(s) are connected to a *wellhead* where valves give access to the annuli. On top of the wellhead a *Christmas tree is installed*, which has valves to control and cut off fluid flow and give access to well intervention work (Figure 1.2). According to the legislation, annulus pressure (ANP) of the inner annuli and the tubing head pressure (THP) shall be monitored on the wellhead. Sometimes, tubing head pressure (THP) and wellhead pressure (WHP) are used interchangeably.

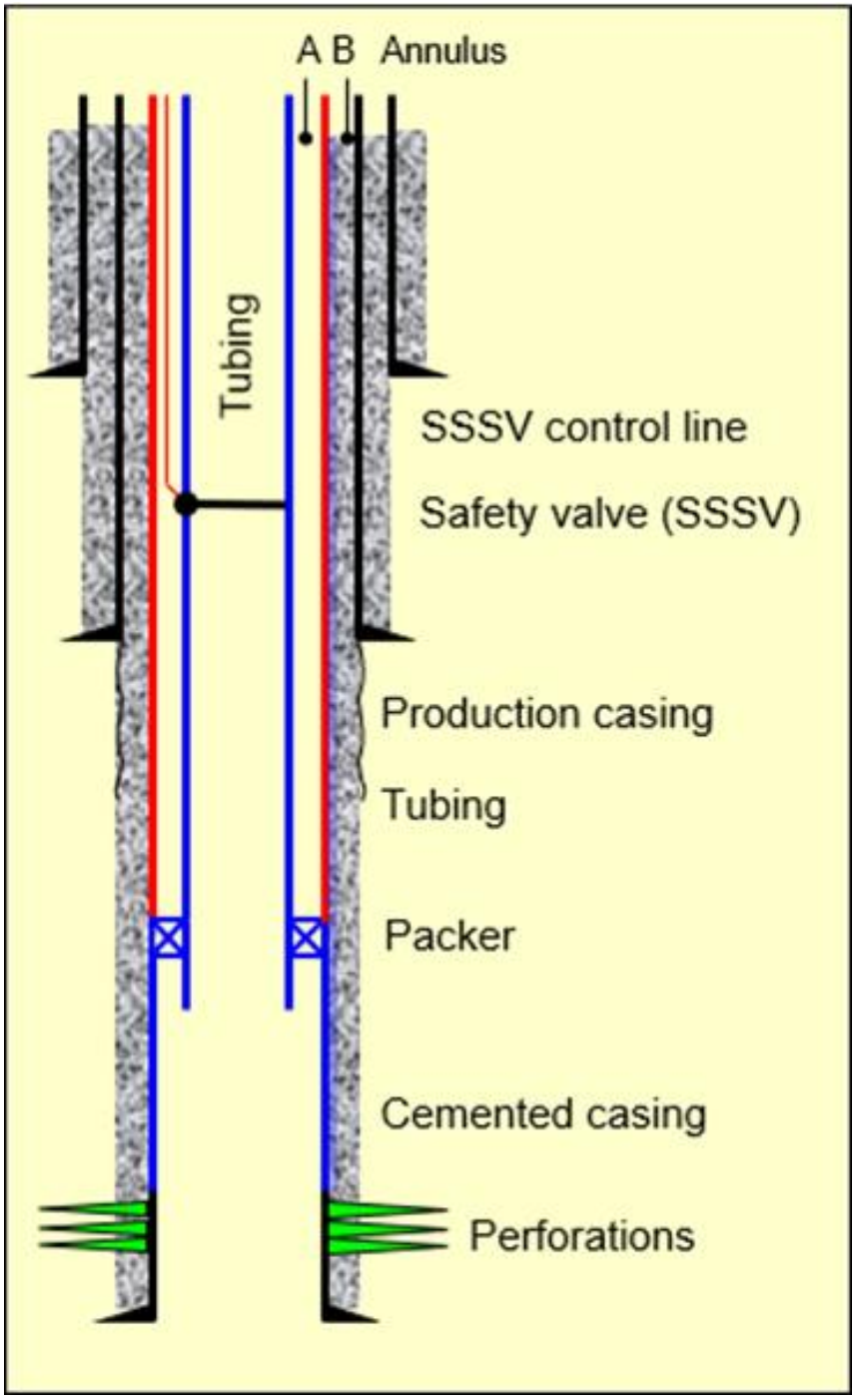

Figure 1.1: Principal diagram of well. Primary barrier is marked with blue, while secondary barrier is marked with red.

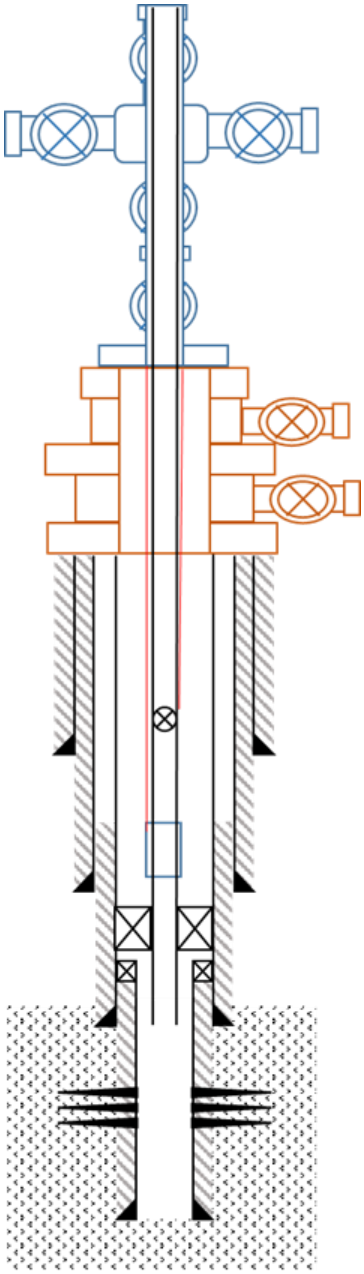

Figure 1.2: Principal diagram of well with wellhead and christmas tree.

2. Operational needs for monitoring (D1.1)

The operational needs for borehole monitoring of CO_2 wells can be divided into three different categories:

1) Monitoring required by regulators/legislation and monitoring specified in relevant standards.
2) Monitoring defined to be necessary by the operator itself.
3) Optional monitoring solutions.

2.1 Minimum requirements for monitoring

The requirements for monitoring in CO_2 wells in Denmark are based on two different legislation schemes, namely the Danish Subsoil Act[1] and the Danish CCS legislative Decree[2]. The first of these defines minimum requirements for deep wells in general and applies to both oil and gas wells and CO_2 wells. The latter is the Danish implementation of the EU CCS directive[3] and defines the necessary data collection needed to prove sound and safe CO_2 storage operations. Thus, the CCS directive does not give specific requirements for monitoring, and therefore it gives the operator some degree of freedom to choose relevant monitoring techniques to obtain the required data. The Danish Subsoil Act does not have any specific requirements for monitoring, but operators are expected to follow accepted and relevant industrial standards.

The data required in the CCS legislative Decree that potentially could be sampled from a borehole can be described as follows:

- Formation water sampling (clause 10.1)
- Monitoring CO_2 migration (clause 10.3)
- Monitoring CO_2 leakage (clause 10.4)
- Volumetric CO_2 flow at wellhead (Annex 2, clause 1.1.f)
- Pressure and temperature at wellhead (Annex 2, clause 1.1.g)
- Reservoir pressure and temperature (Annex 2, clause 1.1.i)

Optional recommended data sampling:

- Methods to detect CO_2 leakage paths
- Monitoring of the horizontal and vertical plume and pressure distributions

2.1.1 ISO standard requirements for monitoring

An operator can choose to follow a relevant standard. The ISO 27914:2017 gives standards for geological storage of CO_2. Below is briefly listed the requirements and recommendations for borehole monitoring and data that potentially could be sampled from a bore-

[1] https://www.retsinformation.dk/eli/lta/2023/1461

[2] https://www.retsinformation.dk/eli/lta/2016/1425

[3] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32009L0031

hole. Note that the ISO standard mostly gives recommendations and high level descriptions, giving the operator the freedom to choose specific methodologies and instruments for measuring.

Requirements:

- Monitoring of the mass of the injected fluid stream
- Tubing head pressure and temperature continuously surveillance (THP, THT)
- Annulus pressure and temperature continuously surveillance of annuli between tubing and casing (ANP, ANT)
- Integrity of tubing and wellbore shall be confirmed, and an inspection procedure shall be in place
- For converted wells: Casing inspection log prior to injection (corrosion and other types of damage).
- Determination of annual average pressure of storage unit
- Cement integrity logs shall be done after cementing.

Optional:

- Baseline gas saturation log prior to injection
- Injection temperature
- Bottom hole pressure and temperature surveillance (BHP, BHT)
- Monitor and evaluation of well integrity tubing and annulus integrity (to ensure no fluid transfer between annulus and tubing and between annulus and geologic formations)
- Wireline logs.

2.2 Operator requirements for monitoring

GSD is currently working on the development of an onshore CO_2 storage facility. As an example of an operator's view on monitoring, we here describe the requirements for monitoring that GSD is considering for a future CO_2 storage site in the following sections. Please note that other operators may have different views on some parts of the monitoring.

2.2.1 Well integrity

The most important principle for a CO_2 storage site is that the CO_2 has to be stored safely with a very low risk of major leaks for millennia. The major risk of a leak from a storage complex is recognized to be through the wells or along the near wellbore area, since the wells are penetrating the claystone seal that otherwise secures the containment of the CO_2. Therefore, it is extremely important to ensure the integrity of the wells at all times. Consequently, all wells will be designed and adhere to the two-barrier principal at all times.

The traditional monitoring techniques are based on what has been used for many years in the oil and gas industry, where the most important are conventional measurements at the wellhead of pressure, flow and temperature of the injection tubing, A-annulus and subsequent annulus (B-annulus) depending on the geology of the specific storage complex.

These measurements are enough to monitor the integrity of the well, but several other techniques are important to have in order to understand and correct potential anomalies. Techniques for this include downhole measurements of temperature and pressure in the injection tubing as well as the annulus. Wireline logs can be used to document corrosion of the well, deformations (ovality), leakages and bonding between the cement and the well.

2.2.2 Downhole monitoring

Even though downhole monitoring is not a specific requirement in the Danish legislation and even though there are only a few requirements for downhole measurements in the ISO 27914:2017-standard, namely pre-injection logs (cement bond log and casing inspection log) and integrity logging of tubing and wellbore, there is many more measurements that in practice are necessary to ensure safe and sound operations. One example is gas saturation logging that can be used to determine the saturation of e.g. CO_2 in the near wellbore reservoir. This can be used to improve the efficacy of the injection as well as to document that no CO_2 flows along the well in unwanted geological formations.

2.2.2.1 Continuous measurements

As a potential CO_2-operator, GSD considers it necessary to have continuous measurements of bottom hole pressure (BHP) and temperature (BHT), near the perforations, since those parameters are important to understand the state and performance of the reservoir, and the modelling of those based on wellhead measurements can be difficult due to the complex phase behavior of CO_2 containing a certain amount of impurities.
Moreover, distributed sensing of pressure and temperature along the well is strongly desired, since these data provides important insight into potential leakages and the phase behavior of the CO_2. GSD sees a great potential in the use of optical fibers for distributed sensing and therefore this is the preferred monitoring method, but other sensing techniques will also be taken into consideration, such as more conventional temperature sensors and pressure gauges.
Finally, the monitoring of potential leakages and the CO_2 plume migration by using Distributed Acoustic Sensing (DAS) with optical fibers will be a great way of ensuring that the CO_2 is contained in the right geological formation(s), and therefore this is also an attractive monitoring method. However, the technology needs to be improved with respect to installation methods in the wells, especially in existing wells, and interpretation of the signals from the fibers which is one of the main focuses of the BOMS project. In Figure 2.1, an example of a new CO_2 injector well designed for GSD is shown, including possible locations for optical fibers for DAS (marked with green).

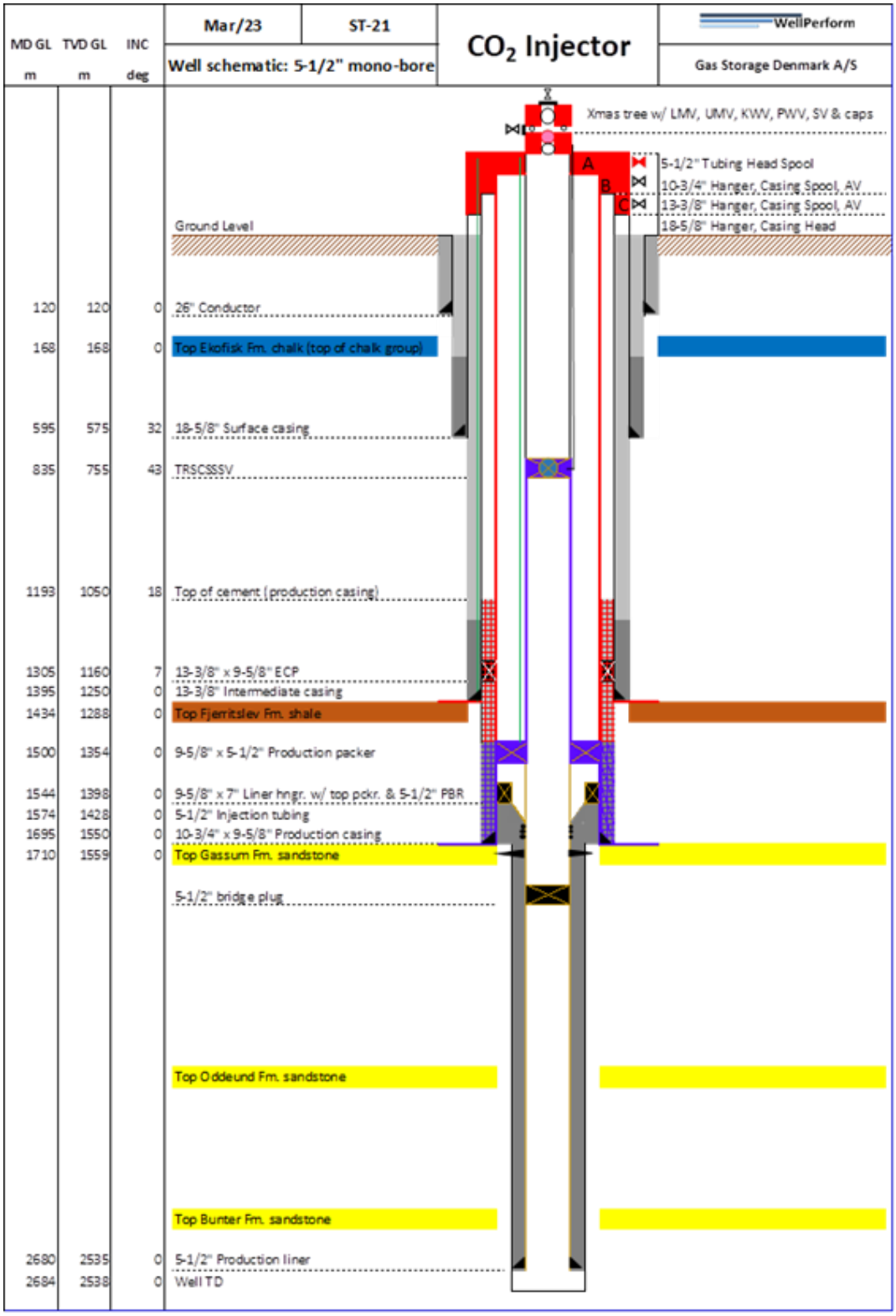

Figure 2.1: Example of design of new CO_2-injector well designed for GSD. The vertical green lines indicate possible locations of optical fibers for DAS.

2.2.2.2 Periodic measurements

Besides the continuous measurements described above, GSD find it necessary to include various types of wireline logs that are run either in fixed intervals or occasionally when there is a need for a specific log. Gas saturation logs and corrosion logs (e.g. multifinger caliper logs or magnetic logs) are desirable to run in fixed intervals because they can then give insight into the evolution of the CO_2 injection in the reservoir and the integrity of the well, respectively. Other logs may also be relevant, depending on actual operational needs.

3. Overview of existing technologies (D1.2)

3.1 Review of existing monitoring technologies for near wellbore monitoring

The DTU report (Appendix 7.1) 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.

3.2 Review of Distributed Fiber Optic sensing (DFOS).

As described in section 3.1 Carbon Storage wells demand robust monitoring to ensure safety, efficiency, and long-term integrity. DFOS technologies like Distributed Temperature Sensing (DTS), Distributed Acoustic Sensing (DAS), Distributed Pressure Sensing (DPS), and Distributed Strain Sensing (DSS) offer a step-change in monitoring capabilities compared to conventional systems.
Unlike discrete sensors, DFOS provides continuous, real-time data along the entire wellbore, delivering:

- Comprehensive Coverage: Detect CO_2 plume migration, casing deformation, and other anomalies across the full well length.
- Real-Time Insights: Monitor dynamic subsurface changes for proactive risk mitigation.
- Integrated Functionality: DTS, DAS, DPS, and DSS in a single, durable system simplify design and reduce costs.
- Long-Term Reliability: Resilient to harsh downhole conditions, ideal for extended monitoring.

With DFOS, this project intends to enhance well safety while meeting regulatory standards and improving performance efficiently and effectively. The Welltec report on DFOS for wells (Appendix 7.2) describes the current state of sensing technologies using optical fibers.

4. Welldesign incl monitoring possibilities (D2.2)

GSD has contracted with Wellperform to design the wells for the Stenlille CO_2-storage project, and the following section on well design has therefore been prepared by Wellperform in collaboration with GSD. Here, conceptual analyses are described; when it comes to specific well designs for a given reservoir and project scope, more detail is needed.

The Stenlille CO_2-storage project was initially designed with two new CO_2 injection wells (ST-21 and ST-22) and re-use of an existing well (ST-6), used by the gas storage site for disposal of produced formation water, as a CO_2-monitoring well. Later, the project was changed to a phased development, using ST-6 for CO_2 injection for phase I and drilling the two new wells and converting ST-6 to a CO_2 monitoring well for phase II. The motivation of the phased development was to enable a fast-track solution to CO_2-storage to meet the needs of the authorities as well as the market.

The well design work on the two new CO_2 injection wells and the design work on re-completing ST-6 first as a CO_2 injection well and later as a CO_2 monitoring well is the basis for the below in describing the options to implement surveillance systems in the wells.

In this section, we focus on permanently installed monitoring systems in the top completion and in the reservoir section of the wells delivering continuous data that can be used for monitoring CO_2 injection into different reservoir layers, CO_2 plume migration in the reservoir and well integrity. Surveillance campaigns during field life using wireline for deploying surveillance tools and tools for downhole fluid sampling is not covered in this report.

4.1 Surveillance Well Design

The description of well designs for surveillance systems in this section is divided into options for the upper and lower completion. The section is describing the various operational considerations which have to be considered for safety reasons when it comes to selection of monitoring technologies for the well design.

4.2 Monitoring technology introduction

4.3 Upper Completion

New wells (ST-21, ST-22):

The fiber optic cable for DAS should be cemented in place with the innermost casing string to obtain maximum connection to the surrounding formation and thereby improve the acoustic signals from the reservoir during injection and plume migration. In order not to risk the integrity of the cement of the 9-5/8” casing set in the top of the reservoir the fiber optic cable should be cemented in place with the 13-3/8” casing in the two new wells, see Figure 4.1. This placement is considered acceptable for reservoir surveillance of the plume migration with DAS.

Existing well (ST-6):

The A-annulus (Production casing/completion annulus) is both for the new wells and the re-completion of ST-6 designed with a conventional pressure/temperature (P/T) gauge above the production packer to monitor pressure and temperature inside the tubing and DFOS fiber optic cables along the tubing to monitor the A-annulus again above the production packer. The reason for installation of DTS and DAS in the A-annulus is in order to hopefully allow for better detection of any leak points in case of a tubing to A-annulus communication. This is field proven standard equipment for oil and gas wells.

In the ST-6 well the clearance between the 5-1/2” casing and the planned 2-7/8” completion is limited and there may not be enough space for running the fiber optic and cables

across the Safety Valve (SSV) and the gauge carrier, where a temperature and pressure gauge will be installed. It may therefore be necessary to use a 2-3/8" SSV and terminate the fiber optic cable above the gauge carrier where the cable also is attached.
The fluid in the A-annulus, also known as completion fluid for oil and gas wells is normally a brine (saline water) mixed with biocide, oxygen scavenger and corrosion inhibitor to protect tubing and casing from corrosion.. For CO_2 wells, the risk of CO_2 ingress into the A-annulus may cause rapid and severe corrosion in carbon steel production casings resulting in loss of well integrity. Monitoring of changes in pressure and temperature in addition to monitoring of acoustics changes which may be caused by CO_2 ingress is therefore important to detect a leak as early as possible to allow for actions to eliminate the ingress. To improve detection of minor pressure response from a CO_2 ingress, N_2-cushion, which is a N_2 column in the A-annulus, may be helpful as cooling during injection may result in vacuum in the annulus which can make pressure variation difficult to detect and analyse.

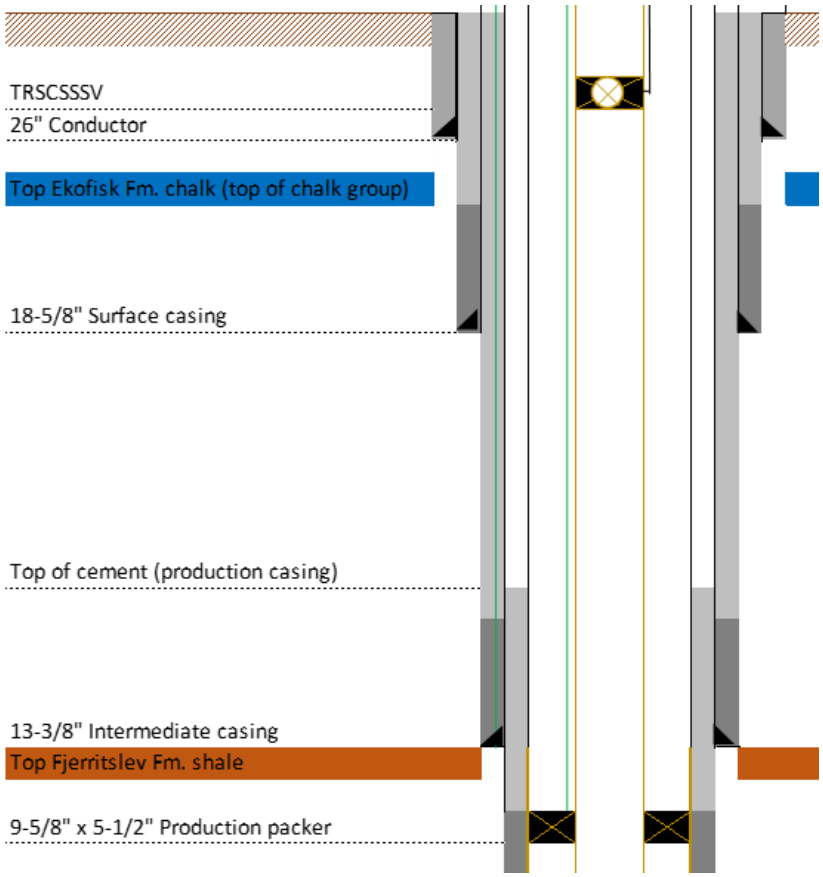

Figure 4.1 Top completion with fiber optic cable in A-annulus and cemented in place in C-annulus.

There is always a risk that the primary barrier is breached and therefore a need to protect the secondary barrier, i.e. the production casing etc. The A-annulus fluid may alternatively be base oil, glycol or other fluid that CO_2 does not react with to cause a corrosive environment. This may reduce the risk of loss of well integrity.

4.4 Lower Completion

In the Stenlille CO_2 storage project, DTS and DAS were desired over the reservoir section to estimate the injection rate distribution into the different zones and to provide additional information of the plume migration. This was considered feasible for the new wells with 7" liner, 9-5/8" production casing and 5-1/2" tubing.

ST-6 has originally been designed with a 5-1/2" production casing from the bottom of the well to surface and planned with 2-7/8" tubing. Due to the limited clearance between casing and tubing and due limited completion equipment options developed for tubing size less than 3-1/2" it was not considered possible to install fiber optic cables in ST-6 reservoir section.

No proven or validated packers for ST-6 for CO_2.were identified on the marked in 2024.

Completion with Wet connector

For mitigating potential well control issues during completion installation it may be required to install the reservoir completion and the top completion in two runs. In the case where fiber optic cables will be installed in the reservoir section, a connector (called wet-connector) between the top completion and reservoir completion is required to establish connection of the reservoir surveillance system to surface (see Figure 4.2).

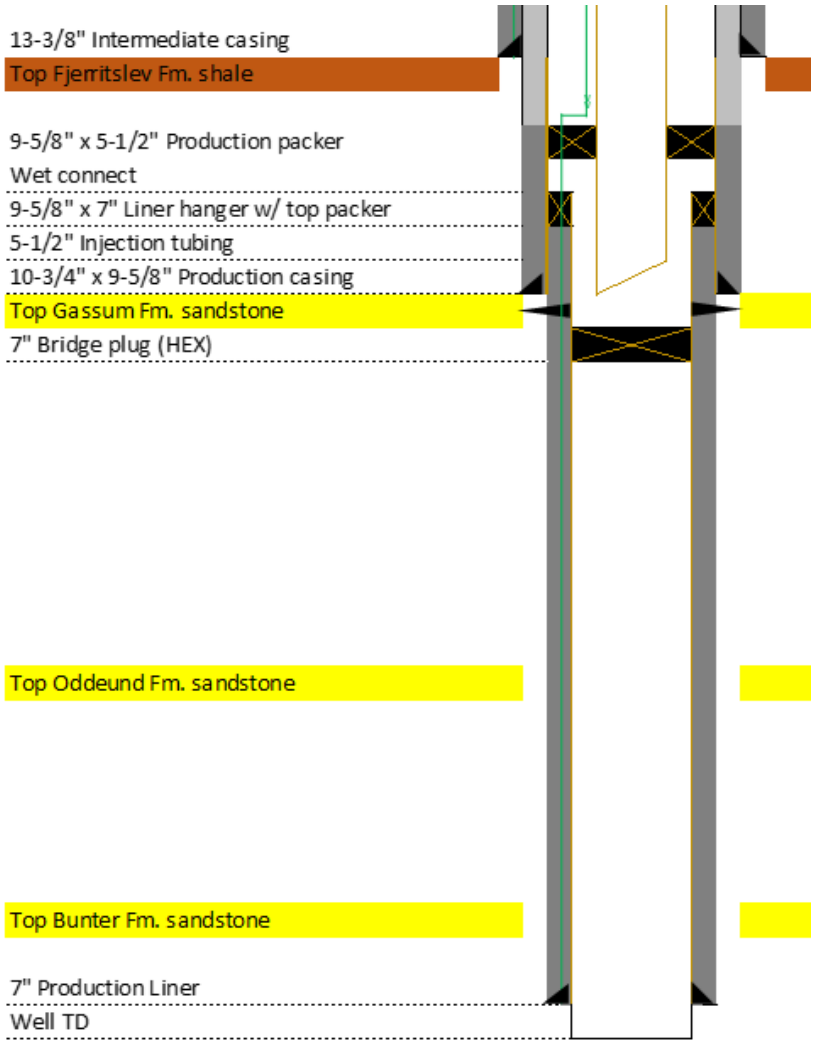

Figure 4.2 Fiber optic cable cemented behind 7" liner and wet connector.

For SMART wells (also known as intelligent wells) Wet-Connect's for electrical and hydraulic systems has been available for some years. Wet-Connects for Fiber Optics do exist but is a relatively immature technology with limited field cases. For the Stenlille CO_2 storage project it was found that the risk of using Wet-Connect for the completion was unacceptable large.

Packer with cable feed-through

Multi-zone SMART (Intelligent completion) was introduced to the oil and gas well completions in the later 1990'ies introducing packers with cable feed-throughs for electrical/hydraulic sleeve manipulation and reservoir surveillance (see Figure 4.3). The systems are common for 3-1/2", 4-1/2" and 5-1/2" completions with limited equipment available for 2-7/8" completion. The multizone reservoir completion is typically run together with the top completion to eliminate the risk of using downhole Wet-Connect below the production packer. This, however, introduces more well control risk during installation of the completion.

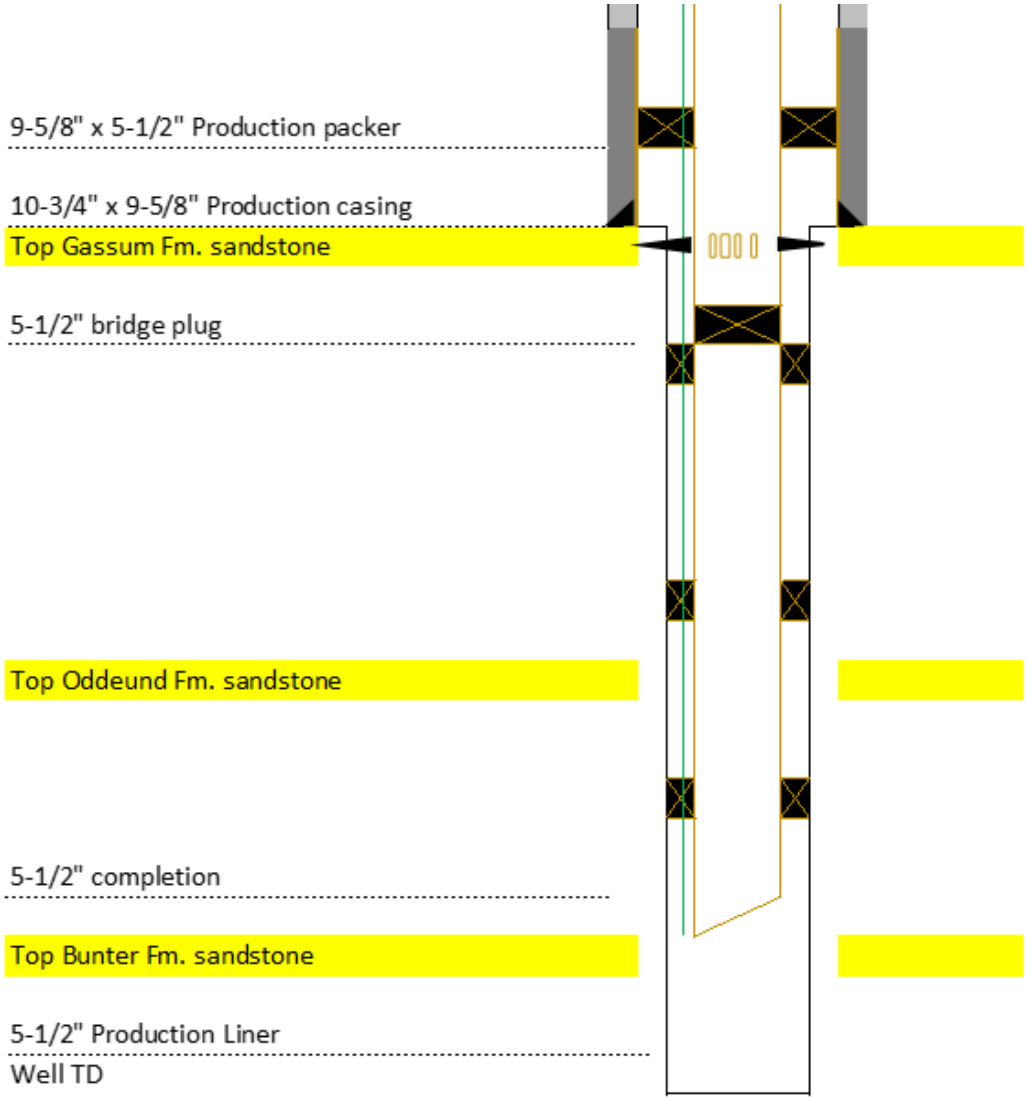

Figure 4.3 Packer with cable feed-through completion

The big service companies (Halliburton, Baker, Weatherford and SLB) have these systems in their product portfolio and a number of mid-size service providers also provide these systems (for example Emerson, NOV, Welltec). The systems are qualified for the oil and gas industry and there are limited feed-through packers qualified for CO_2 yet available on the market due to the immaturity of this industry.
The two wells, one injection well and one monitoring well, on the Decatur Basin CCS project in Illinois were both completed with 5 packers with feed-through for DTS and DAS fiber optic cables. The DTS and DAS system was part of the Intelligent completion installed and was delivered by SLB. The monitoring well was equipped with gas lift valves enabling production for surface fluid sampling from the individual zones using N_2 lift.

Wireless Telemetric
Wireless telemetry was developed for HPHT wells around 1990 to transmit data during well testing from the harsh HPHT reservoir environment to surface to reduce well integrity risk. The systems have developed over years and recently also been addressing CCS wells (see Figure 4.4).
The system gathers data from gauges and fiber optic metering systems installed below the packer(s) to surface using transmitters and receiver stations every approximately 500 meters. As the data is transmitted wirelessly there is no cable penetration in the packer or well head and the associated potential leak paths are hence eliminated. The transmitter and receiver stations are powered with lithium battery packages which may last more than 8 years in service. A hybrid system comprises of a transmitter-receiver station above the production packer where the data is transmitted further to surface via a mono-conductor cable.

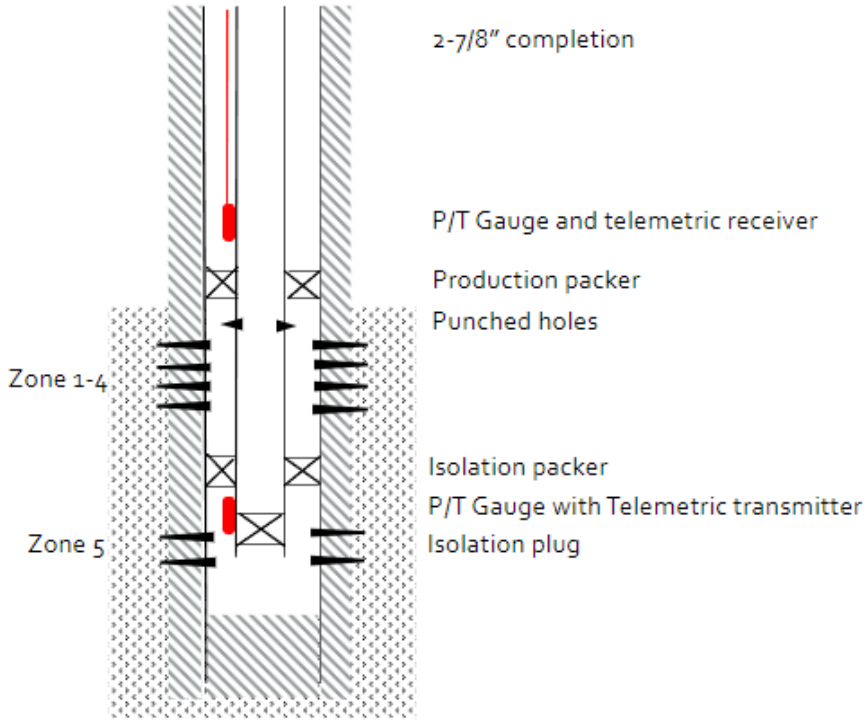

Figure 4.4 Wireless telemetry for transmitting data

Niche companies Metrol and Acoustic Data have been delivering these systems for years but also SLB has wireless telemetry in their product portfolio.

5. Gap analysis (D2.1)

The review in section 3.1 and 3.2 has been compared to GSD well design and monitoring possibilities in section 4.

As described in section 4 the installation of DAS fibers as part of the well design poses a challenges as the fiber in the cement creates a potential leak path. There are various way of designing around the installation challenge but focus will have to be on avoiding to add additional leak risks by adding monitoring solutions to the well design.
Using DAS for monitoring the progression of CO2 through the formation is relatively mature and ready for implementation. There is however, a gap in understanding the elastic and acoustic response of the formation and cement to CO_2 saturation. This knowledge is necessary in order to interpretating the DAS signals and thereby enabling the detection of a moving CO_2 plume.

6. Experimental reasoning

Downhole monitoring of CO_2 storage sites, where boreholes are cased, can be done on a continuous basis by using optical fibres for collecting information on strain and elastic wave velocity in the formation and in the cement enclosing the casing. The main unresolved questions are however, how to interpret the resulting information.
Rock physical inversion is an obvious choice, but it is not straight forward to define which models are optimal for each relevant lithology. In order to address this, we recommend laboratory experiments, where CO_2 is injected into known lithologies and the experiment is monitored by measuring strain and elastic wave velocities. In this way the results from inversion can be compared with known values.
The information we seek is CO_2 saturation and elastic strain: CO_2 should not leak from the reservoir and elastic strain should not cause fracturing. In a Danish context, relevant lithologies are: sandstone, chalk, shale and cement.

7. Appendices

In this document, paste in summaries of every report and make the connections. The individual reports are in as appendices.

7.1 DTU report

7.2 Welltec report