CATO-2 Deliverable WP3.4-D17 Monitoring Strategies for Inaccessible/Abandoned Wells

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1 Executive Summary (restricted)

Underground storage of CO_2 in depleted oil reservoir and deep saline aquifers is considered as an efficient way of reducing greenhouse gas emissions. Ensuring the safety and integrity of the storage site is crucial for such an operation. Abandoned wells have been identified as the biggest threat to the integrity of CO_2 underground storage sites, mainly due to concerns about the regulations and industry standards at the time of abandonment. Another issue is that abandonment might have been performed due to problems that occurred during the life cycle of a well which indicate reduced integrity in the first place. Continuous monitoring is needed throughout the project to confirm that the integrity of wells in the storage compartment has been maintained. This report discusses the risks associated with abandoned wells, evaluates existing technologies to monitor abandoned wells and summarizes options to mitigate fluid flow along or out of abandoned wells if a leak was detected.

In the Netherlands, most regulations concerning well abandonment date back to 1964, even though an updated Mining Act has come into effect as of 2003. According to current regulations, permanent cement barriers (cement plugs) of at least 100 meter thickness are placed on top of every reservoir section and around each casing shoe during abandonment. Furthermore, the casing is cut to 3 meters below ground level (or 6 meters below sea floor in an offshore well), and a surface plug of the same configuration is placed to close the well off. Alternatively, a combination of a mechanical plug and a 50-metre cement plug placed on top is also sufficient. However, wells abandoned earlier mostly do not match these requirements and are not in compliance with modern abandonment practices so that they present potential risks for the containment of the injected CO_2.

Potential leak paths in an abandoned well may be present along the cement - formation interface, cement - casing interface or through cracks in the cement. These are usually generated due to poor cement placement, improper abandonment and casing failure.

Injection of CO_2 increases the probability of leakage, and can form new potential leakage mechanisms within the (storage) system. Reservoir decompaction during injection might result in the formation of additional annular space due to debonding of the casing cement interfaces. Additionally, dissolved supercritical CO_2 is corrosive to both cement (cement degradation) and casing (steel corrosion), and may generate additional pathways either through the used materials or along their interfaces.

Monitoring of (abandoned) wells can either be direct or indirect. For direct monitoring, there are several available logging methods and downhole sensors that can be applied in the wellbore. However, to deploy these in an abandoned well, it is necessary to re-enter the well first, which is costly and can often be technically challenging. Therefore, indirect methods for monitoring of abandoned wells are used in most cases. Indirect methods comprise various geophysical survey techniques conducted either on the surface or from another well (cross-well or well-to-surface measurements). Other monitoring methods include CO_2 sensors placed in shallow subsurface or at the surface, and various chemical and biological tests to detect leaks at sea-bottom or the surface. One of these leakage detection methods, the streaming potential (SP) method has been studied further to investigate its applicability in CO_2 storage projects. This method presents a promising option to detect relatively shallow leakages, but amplitude issues inhibit to apply this technique in the deeper subsurface.

Depending on the consequences of the leakage, remediation might be deemed necessary for either environmental and/or economic reasons. Remediation options for abandoned wells are quite limited and comprise locating the cut-off casing, re-entering the well, stopping the leakage and re-abandoning the wellbore. Well records and either wide-scale or ground level geophysical surveys are used to locate the cut-off casing. It is important here to use methods that are sensitive to detect steel/cement. To re-enter the well, the steel plate on top of the well, the surface plug and all other plugs that block the access to the location of the leak have to be drilled out. In case it is not possible to re-enter the existing well, a new well that provides access to the leaking well interval should be drilled. Regardless of the operation, a drilling rig will be required to gain access to the well.

Different remedial actions can be deployed depending on the location of the leak. For a leak in the annulus between the casing and the formation, cement squeeze operations are usually performed. If one of the plugs is found to be leaking, the plug should be replaced. The recommended practice in such cases is to install a fullbore formation plug. These plugs can also be used to remediate leaks in the annulus. After remedial actions are finished, the well has to be re-abandoned according to latest regulations by reestablishing the integrity of the penetrated natural sealing formations (cap rocks).

Remediation of abandoned wells is a costly and time-consuming practice mainly due to the necessity of a drilling rig and crew. For an onshore well, the costs may add up to a few million Euros, and significantly more for an offshore well if a delicate remediation is required. Due to the economic burden, remediation operations are conducted only in the presence of an immediate risk for humans/ environment or due to expected financial benefits.

A part of the study is dedicated to design a general monitoring strategy for abandoned wells. The strategy covers three phases of the CO_2 storage project: pre-injection, injection and post-injection. The pre-injection tasks start with the characterization of the site and the assessment of all potential risks related to wells drilled through the storage site. As a result of the site characterization phase, a monitoring network that encapsulates particularly all abandoned wells penetrating the cap rock/target formation is installed and monitoring commences by taking baseline surveys.

Monitoring during CO_2 injection is carried out with frequent, repeated surveys coupled with continuous monitoring through sensors. It is important to establish a flexible network that can be easily adapted and maintained depending on the progress of the project. The monitoring efforts for abandoned wells are only a part of a wider monitoring obligation within the entire project. Therefore, making use of the whole monitoring network and other aspects of the project such as simulations will ensure a more sophisticated and efficient monitoring plan.

Once a leak has been detected, its consequences and exact location must be determined before a decision about remediation is being made. If re-entering the well and remediation is an option, direct monitoring methods can be applied and installed in the re-opened well.

After injection has been stopped, monitoring needs to be continued until it is ensured that the field evolves towards a (predicted) stable state and no leakage occurs. Monitoring an abandoned well only provides information if this particular well is leaking, but it is unlikely to provide other relevant information. If applicable, a previously abandoned well can be remediated and turned into a monitoring well. Stabilization of the site will be confirmed by additional monitoring methods, which have to be suited to site-specific aspects (e.g. microseismics or groundwater monitoring).

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Document Change Record

(this section shows the historical versions, with a short description of the updates)

Version	Nr of pages	Short description of change	Pages
1		First draft	38
2		Final public version	68

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2 Applicable/Reference documents and Abbreviations

2.1 Applicable Documents

(Applicable Documents, including their version, are documents that are the "legal" basis to the work performed)

	Title	Doc nr	Version
AD-01d	Toezegging CATO-2b	FES10036GXDU	2010.08.05
AD-01f	Besluit wijziging project CATO2b	FES1003AQ1FU	2010.09.21
AD-02a	Consortium Agreement	CATO-2-CA	2009.09.07
AD-02b	CATO-2 Consortium Agreement	CATO-2-CA	2010.09.09
AD-03g	Program Plan 2013b	CATO2-WP0.A-D03	2013.04.01

2.2 Reference Documents

(Reference Documents are referred to in the document)

	Title	Doc nr	Version/issue	Date
	Development and feasibility study of advanced materials/treatments for abandonment and mitigation	CATO2-WP3.4-D10	Public Report	31/12/2013
	Evaluation of current logging tools and industry practices for material selection and repairs	CATO2-WP3.4-D15	Public Report	13/02/2012
	Specifications and design criteria for innovative corrosion monitoring and (downhole) sensor systems	CATO2-WP3.4-D16	Restricted	31/12/2013

2.3 Abbreviations

(this refers to abbreviations used in this document)

$CaCO_3$	Calcium Carbonate
CBL	Cement Bond Log
CCS	Carbon Capture and Storage
CET	Cement evaluation tool
CMT	Cement mapping tool
CO_2	Carbon dioxide
DHV	Downhole video
DTS	Distributed temperature sensing
EPA	United States Environmental Protection Agency
FFP	Fullbore Formation Plug
GPR	Ground Penetrating Radar
GS	Geologic sequestration
IEA	International Energy Agency
IEAGHG	International Energy Agency Greenhouse Gas R&D Programme
IPCC	Intergovernmental Panel on Climate Change
IRGA	Infrared Gas Analyzer
K	Hydraulic conductivity (m/s)
L	Electric current density (A/m^2)
NDIR	Nondispersive Infrared Sensor

PMIT	Platform Multifinger Imaging Tool
SP	Self (Streaming) Potential
UIC	Underground Injection Control
USI	Ultrasonic Imaging
V_{thr}	Amplitude of anomaly
VSP	Vertical Seismic Profile

3 Introduction

When a potential site for Carbon Capture and Storage (CCS) is evaluated in an area where previous drilling operations have taken place, e.g., oil and gas, geothermal or solution mining, one of the essential steps of ensuring the integrity of the storage location is to assess all wells in the storage compartment. Especially, the wells penetrating the storage formation and the sealing formation are important, as they may provide a leak path for the CO_2 stored in the reservoir.

Under typical downhole conditions for CO_2 underground storage, the casing and cement in wells are susceptible to corrosion and degradation by $CO_{2.}$ This can lead to a loss of integrity of both active and abandoned wells. However, in most cases, where a proper abandonment was carried out, the effects of corrosion and degradation are not expected to pose a problem. The integrity of previously abandoned wells is of specific interest, since any remediation work requires locating and re-entering the well which is costly and can be technologically challenging. All wells are finally abandoned in their normal life cycle. For a minor part, the reason for abandonment could be problems that have occurred during construction or operating life, and therefore may impose an additional risk of reduced well integrity. Furthermore, the industry standards and regulations at the time of abandonment might be not as sophisticated as current standards; thus increasing the possibility of integrity issues. Problems such as lack of detailed well and monitoring data due to age will also feed into the evaluation of the storage site. Thus, when ranking reservoirs for their capacity to be used for CO2 storage the presence of decommissioned (abandoned or suspended) wells should be considered. If abandoned wells are present in a field or aquifer for potential CO2 storage, that have insufficient information available they represent a risk or costly component in the project.

To ensure the integrity of a CO_2 storage site, monitoring is required. With accurate and timely monitoring it is possible to detect irregularities and to take necessary actions. Many conventional methods do exist to monitor the integrity of active, accessible wells. This topic is beyond the scope of this study and is addressed in another deliverable within CATO-2 SP3. The aim of this deliverable is to evaluate the applicability of current monitoring techniques for inaccessible/abandoned wells, and to establish a strategy to monitor these wells. Monitoring strategies used in existing CSS projects around the world are examined. As remediation will be inevitable in the presence of complications, remediation options and their potential costs are also discussed.

3.1 Well Abandonment

When a well approaches the end of its operational life, abandonment operations ensue. The purpose of well abandonment is to isolate the reservoir formations and to prevent leakage, either towards the surface or towards surrounding formations. Abandonment aims to restore the natural integrity of the formation that was drilled into by installing permanent leak barriers inside the wellbore.

Depending on operational decisions, the operator may decide to either temporarily -also called “suspend”- or permanently abandon the well. However, if no further operations are planned on the well, permanent abandonment must be performed. The main difference between permanent and temporary abandonment is the removal of the wellhead during permanent abandonment. With the wellhead removed, direct monitoring of parameters within the wellbore is not possible, and certain measures have to be taken to re-access the well for remedial work. Regardless of the type of abandonment, multiple barriers are installed in the well to ensure integrity. This study focuses only on permanently abandoned wells; suspended wells will not be discussed in this report.

The industry best practices for well abandonment are constantly amended by technological developments or new procedures. With an increasing number of gas storage projects, recent practices have been focusing on solving problems that may rise during these operations; e.g. corrosion of tubulars. Well abandonment is regulated by governmental agencies based on these best practices. Current regulations for well abandonment in the Netherlands are summarized in section 4.1.2. The problem with previously abandoned wells is that the industry standards at the date of abandonment may not match current standards and thus are more susceptible to leaks. Possible leak paths in an abandoned well are discussed in Section 4.2.

3.2 Monitoring

Monitoring a CCS project is required for the following reasons (Directive 2009/31/EC, 2009)

1. **Safety and environmental protection reasons:** It is of utmost concern to ensure that the people, animals and the ecosystem are not harmed.
2. **Societal reasons:** The public should be informed about the details of the safety of the storage operation in order to establish trust within the population.
3. **Financial reasons:** The amount of CO_2 stored must be monitored as accurately as possible to be written off as “prevented emissions.”
4. **Operational reasons:** For controlling and optimizing the injection process.

The first of the above reasons is the main concern for monitoring abandoned wells. Injected CO_2 may leak out of the target reservoir via faults, fractures or wells. Adequate monitoring ensures an immediate detection of leakage. Consequently, adequate countermeasures can be defined and any (potential) damage can be minimized.

Monitoring methods can be either direct or indirect. Direct monitoring methods consists mainly of installing tools in the wellbore to conduct measurements (also known as logging). Sampling at the surface and near surface is also another way of direct monitoring. However, these methods are only effective in detecting the presence of a leak rather than pinpointing where the leak is located. Indirect monitoring techniques on the other hand include various seismic and non-seismic geophysical and geochemical methods.

There are a number of readily available monitoring tools and methods that can be used to monitor well integrity. However, most of these methods are only applicable to injection or monitoring wells. Those can only be used to monitor abandoned wells when the well is re-opened. Chapter 5 of this report will provide an overview of current monitoring techniques, and discuss their suitability in monitoring integrity of previously abandoned wells. Innovative monitoring techniques that are currently in their development stage will also be a part of this chapter.

3.3 Remediation and Re-abandonment

Any leakage of CO_2 from the storage formation needs to be detected and evaluated as early as possible. The leaking gas will migrate upwards and will eventually be released into the water column, groundwater or the atmosphere, all of which could cause environmental issues. In case the amount of leakage is substantial, the benefit of decreased gas emission is significantly reduced. Furthermore, when migrating CO_2 dissolves in formation water, it may lead to an increased amount of trace metals in the water (Wang & Jaffe, 2004). This contamination may induce health risks for humans when ingested. Certainly, such an occurrence would also have negative effects on the public opinion about CCS projects and may eventually lead to the cancellation of the project or technology as such. To avoid this, remedial action should be undertaken when necessary.
Various options are available for remediating active or accessible wells. Remediation of previously abandoned wells on the other hand would comprise locating, re-entering and re-plugging the well. Additionally, remediation methods to mitigate the contamination caused by the leakage have to be conducted, if required. However, the later techniques are outside the scope of this study. The necessity, practice and costs of remediation of abandoned wells in CCS will be described in Chapter 6.

4 Well Abandonment and CO_2

Well abandonment makes use of permanent barriers to isolate penetrated permeable layers from each other and from the surface. According to a report prepared within the EC FP-7 project CO_2CARE(Wollenweber, 2012), proper well abandonment should:

1) Prevent all physical hazards potentially induced by the well.
2) Prevent any migration of contaminants between various formations.
3) Prevent the possibility of hydrologic communication between originally separated aquifer systems.

Improper abandonment will result in the generation of possible leak paths for the stored gas. These leak pathways would then compromise the isolation of the layers and can result in contamination of subsurface, soil or air. Due to its corrosive nature when dissolved or supersaturated, CO_2 environments such as a CO_2reservoir pose additional risks to the (chemical) resistance of abandoned wells against degradation and corrosion of well barrier materials.

As previously abandoned wells are the subject of this study, well abandonment methods will not be discussed in this report. In recent years, IEA-GHG (2009) and CO_2CARE (2012) have published reports about well abandonment in which this topic is discussed in detail.

This chapter describes the configurations of abandoned wells that can be encountered on a potential storage site. To serve this purpose, well abandonment regulations (particularly in the Netherlands) are discussed in 4.1. Potential leak paths generate during abandonment operations are discussed in 4.2. This section also explains the mechanisms that might lead to the formation of these leak paths.

4.1 Abandonment configuration and regulations

An abandoned well configuration usually consists of a surface casing that extends below the lowermost drinking water aquifer, and a number of production tubings penetrating the target formation with annuli between different casing strings and between the formation and cemented casing (IEA GHG, 2009). The isolation of layers is secured by installing well barriers that prevent the migration of fluids from the formation (Figure 4.1). The number and properties of these barriers depend on the well construction, the well abandonment procedures and regulations that are employed by the country/state in which the well was spudded as well as on the geological structure of the field. To complete the abandonment, the wellhead is removed and the surface casing is cut to a certain extent to sever any direct connection between the well and the surface.

4.1.1 Class VI Wells

In 2011, the United States Environmental Protection Agency (EPA) has specified a new well class (Class VI wells) for CO_2 sequestration purposes. Class VI wells are defined as injection wells that are to be used in a geologic sequestration (GS) project. As part of their Underground Injection Control (UIC) program, EPA has developed criteria for site characterization, construction, operation, monitoring, remediation and abandonment of Class VI wells (EPA, 2012). In summary, Class VI wells:

- Must be constructed using materials that can withstand contact with the injected CO_2, and any formation fluids that may be encountered at the site. The guidance covers all wellbore materials including cement, tubing and packers. The characteristics of the formation fluid and injected CO_2 must be analysed in order to confirm the compatibility of material.
- Must be designed for the lifetime (including post-injection phase) of the project.
- Must prevent movement into or in between underground supply of drinking water.
- Must be cemented to surface.
- Must be plugged and abandoned using materials that can withstand contact with CO_2 and the formation fluid.

In a storage site, most abandoned wells would have been abandoned without considering the possibility of geologic storage and the well getting in contact with CO_2. Therefore, especially the specifications of material used in these wells could be sub-standard compared to Class VI wells, which increases the risks of insufficient integrity of a storage site.

4.1.2 The Netherlands

Mining regulations in the Netherlands have most recently been updated with the Mining Act of 2003 which contains rules regarding the exploration and development of mineral resources. However, the regulations concerning well abandonment have not been updated in this recent document. The most recent version of these regulations dates back to 1964, when drilling operations were first included in the Mining Act. About 1140 wells have been drilled in the Netherlands before the regulations were updated to include drilling operations (IEA GHG, 2009). In the Mining Act of 2003, Article 8.5 of Mining Regulations of the Netherlands (Mijnbouwregeling) deals with well abandonment (Dutch Mining Act, 2003).

4.1.2.1 General

Generally, the regulations indicate that the fluid in the wellbore should not induce corrosion and should be dense enough to withstand maximum expected borehole pressure. Furthermore, the selected plug should be durable and properly installed. The well barrier can be a mechanical device, a cement plug or a combination of the two. The integrity of the well barrier is confirmed by the following tests:

- Weight test of at least 100 kN (corresponding to a mass of 10250 kg)
- Pressure test of at least 50 bars applied for 15 minutes, or
- Inflow test to confirm that no fluid flows into the well from the formation.

Regardless of the configuration and geological structure, the wellhead needs to be cut off to 3 meters below ground level or 6m below the seafloor and a cement plug of at least 100 meters (or a mechanical plug with a 50 meter thick cement plug above it) needs to be installed under the cut off part of the casing. Furthermore, if there is any suspicion that a mechanical plug in the well may come in contact with a corrosive fluid, a cement plug with a minimum thickness of 50 meters must be placed on top of that mechanical plug.

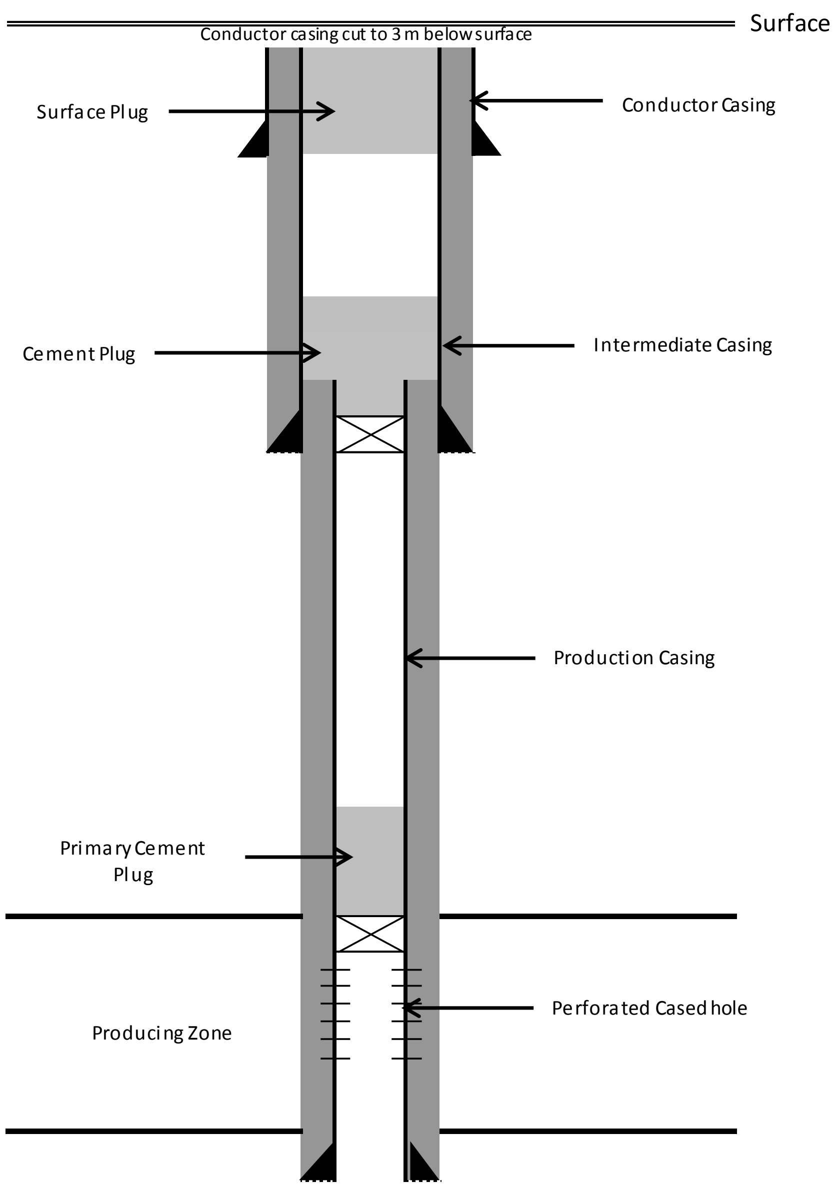

Figure 4.1 Schematic of a permanently abandoned well

4.1.2.2 Partially Uncased Hole

When abandoning a partially cased hole, a cement plug with a minimum thickness of 100 meters should be installed from the lowermost casing shoe. If a mechanical plug is also used, a cement plug of 50 meters or more would be sufficient (Figure 4.2i).

If the target reservoir is located in the open hole section of the well, a cement plug of unspecified length should be placed either at the reservoir level or on top of the reservoir. When more than one reservoir formation is present, a cement plug of at least 100 meters (or natural distance between formations) is placed in between these sections to provide zonal isolation (Figure 4.2 ii).

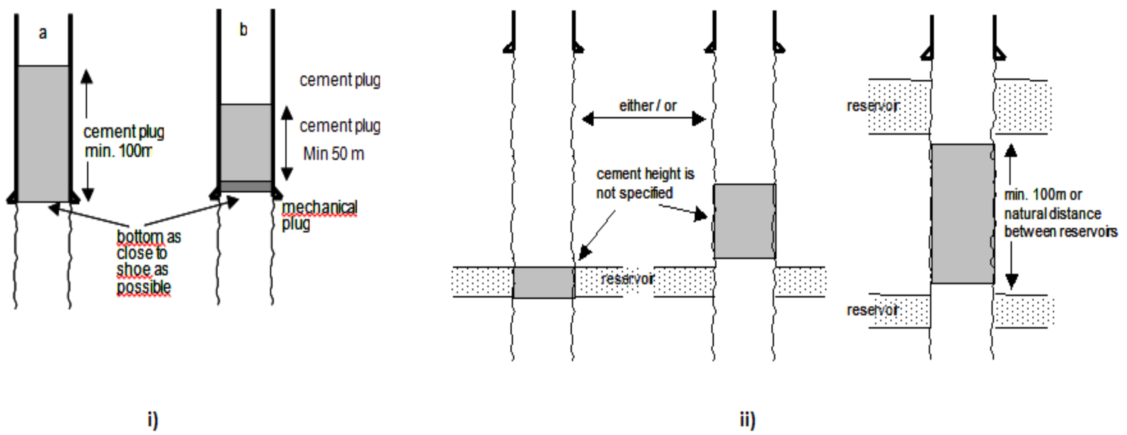

Figure 4.2 Abandonment schematic in a partially uncased hole; i) Plugging lowermost casing shoe, ii) Target reservoir located in open hole section

4.1.2.3 Perforations in Cased Hole

In a perforated hole, a 100 meter-thick cement plug placed above the top perforation would provide a sufficient well barrier. Alternatively, a mechanical plug combined with a cement plug of at least 50 meters can be used. When the latter setup is used, additional cement may be squeezed through the perforations if necessary (Figure 4.3).

If more than one perforated reservoir interval is present, zonal isolation between these is obtained by placing either a cement plug of at least 50 meters (or natural distance between formations) or a mechanical plug on top of the lower interval.

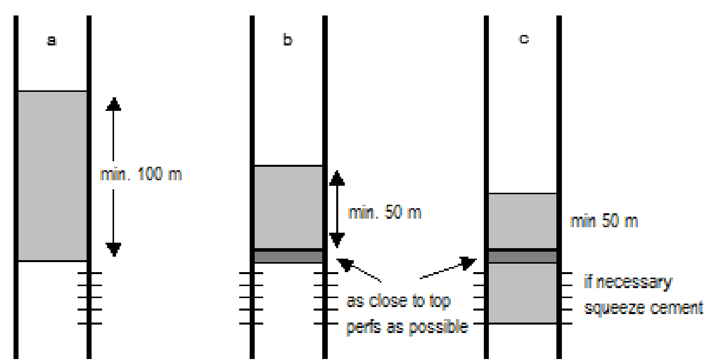

Figure 4.3 Abandonment schematic for perforations in cased hole

4.1.2.4 Cemented Liner

When abandoning a well that contains a liner cemented to the casing a cement plug that extends 50 meters above and below liner is placed in the well. If a mechanical plug will be used, it should be placed approximately 10 meters into the liner and should be followed by a cement plug that extends to 50 meters above the liner. Alternatively, a second mechanical plug installed as close as possible to the top of liner may be used instead of this cement plug (Figure 4.4).

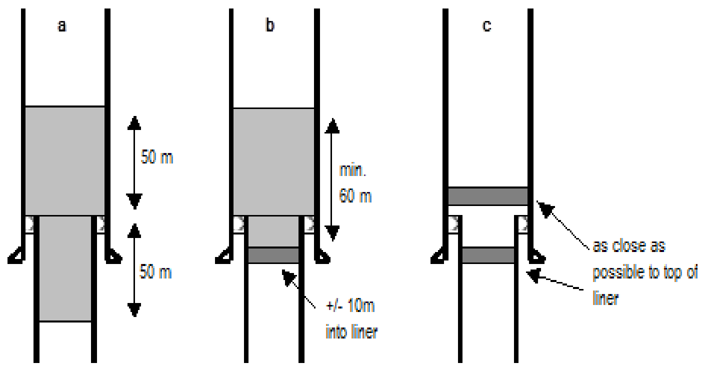

Figure 4.4 Abandonment schematic for cemented liners

4.1.2.5 Annular Spaces

In every annular space between two sets of casing, a seal that extends upwards at least 100 meters from casing shoe of the wider section should be placed. Furthermore, it should be demonstrated that the placed seal is in fact sealing by methods mentioned in Section 4.1.1. If the sealing quality cannot be confirmed, either,

- The inner casing should be perforated at the shoe depth of the previous casing, and a cement plug of at least 50 meters should be squeezed through the perforations. This operation is then followed by a pressure test to confirm that the plug is sealing.

or

- As much of the inner casing within the outer casing should be cut and reclaimed. After reclamation, the well should be treated as a well with a cemented liner and plugged accordingly.

4.1.2.6 Implementation of the EC CO_2 Storage Directive and OSPAR Guidelines into the Dutch Law

A regulation to amend the existing Mining Regulation with respect to underground CO_2 storage entered into force on 16 September 2011 (Dutch Mining Act Update, 2011). The new regulation is based on the EC CO_2 Storage directive (EC, 2009) and the OSPAR Decision 2007/2 on the storage of carbon dioxide streams in geological formations (OSPAR Commision, 2007). This will increase the safety standards of current and future wells in CO_2 environments in the Netherlands, but has no effect on inaccessible wells abandoned prior to this date. For details regarding the new requirements for CO_2 storage wells, please refer to the respective regulation.

4.2 Leak Paths

In potential, numerous pathways for fluid leakage are present in an abandoned well (Figure 4.5). These pathways can occur between the plug and the formation or between the plug and the casing or through the plug itself (Celia & Bachu, 2003). Under normal circumstances, any of these leak paths may be generated because of:

- Poor initial cement sheath during completion,
- Casing failure, and
- Improper abandonment (Watson & Bachu, 2009)

The probability of a leak path significantly increases for abandoned wells penetrating a CO_2 storage formation, due to increased pressure regimes and continuous exposure to corrosive fluids. If the selected storage site is a depleted hydrocarbon field, the pressure in the reservoir may increase during CO_2 injection due to aquifer drive. This will lead to the decompression of the well with tensile loading of the casing (Wollenweber, 2012). Furthermore, the injected CO_2 in combination with formation water will attack the casing and the cement causing corrosion and degradation.

4.2.1 Cement Issues

Prior to abandonment, the well is completed by cementing all annuli of the cased sections of the wellbore, including suspended casings such as liners. Theoretically, in a properly completed well, the quality and integrity of the cement is confirmed by log results and tests, and no issues concerning the quality of cementing should arise. However, even a good cement bond log cannot guarantee complete integrity of the cement sheath (Carey, et al., 2007). The quality of the cement sheath is especially an issue in older wells with no data on completion and abandonment. The cement sheath may not completely seal off the annular space due to the following:

- Cement loss: Cement lost to the formation during cement placement operations will result in small micro-annuli between the formation and the casing due to uncemented sections. Cement losses occur when the annular hydrostatic pressure exceeds the formation pressure.
- Insufficient mud-cake removal: In the process of drilling, the drilling mud invades the formation while some solids in the mud are left behind on the wellbore wall to form a mud-cake. Failure to remove the mud-cake before cementing will lead to creation of annuli between the casing and the formation. The quality of mud-cake removal depends on the amount of pre-flush, pumping speed and hole geometry.
- Casing centricity: If the casing is eccentric (and not centralised), the cement will not be distributed evenly around the casing. This may cause poor removal of drilling fluid which results in the formation of mud channels. Furthermore, parts of cement may be contaminated due to the drilling fluid and micro-annuli could emerge. These issues can be minimized by using casing centralizers.
- Hole angle: Cementing practices are considerably more difficult in high-angle or horizontal wells. Due to gravitational effects, the heavier cement tends to move to the lower side of the well leaving the drilling mud unaffected on the upper side. This may result in cement being absent from parts of the upper half. A reservoir or aquifer with a large number of very deviated decommissioned wells may be eliminated for CO2 storage duty, because the perceived risk of leakage is unknown and maybe high.
- Cement shrinkage: Throughout the hydration of all standard cement classes, about 5 % bulk shrinkage takes place, first of the liquid slurry and later of the solid cement. Cement shrinkage causes circumferential fractures behind the casing (Dusseault, Gray, & Nawrocki, 2000). Formation gas may accumulate within these fractures, and more pressure will be exerted on the cement from below, causing the fracture to propagate upward. Gas leakage may gradually occur from these fractures years after the well is abandoned (Zhang & Bachu, 2011).
- Gas cutting: The initial hydrostatic pressure transmitted from cement within the annulus starts to decrease during cement hardening. If this pressure drops below the formation pressure, fluid influx occurs. This influx will percolate through the cement and create channels that would impair seal integrity.

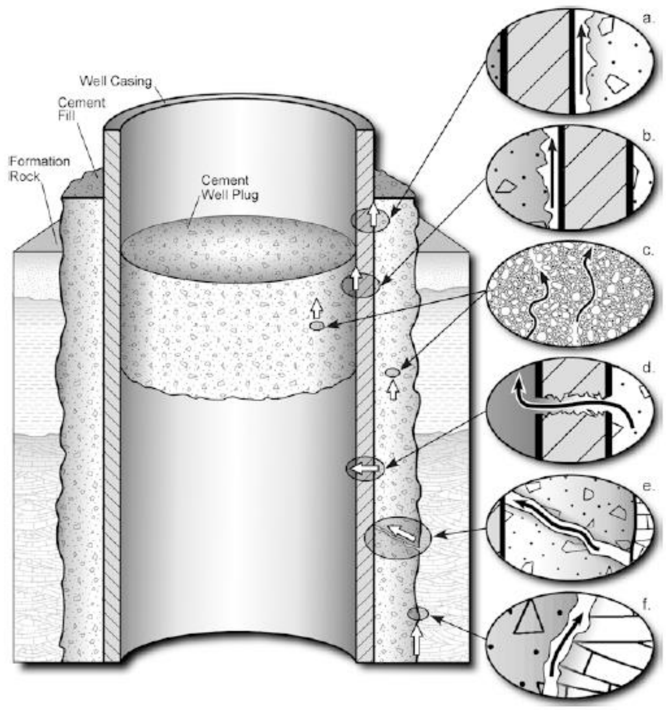

Figure 4.5 Potential leak paths in an abandoned well, (a) through the annulus between casing and cement; (b) through the annulus between plug and casing; (c) through the cement plug; (d) through corroded casing (e); through cement fractures (f); through the annulus between formation and cement (Gasda, Bachu, & Celia, 2004)**.**

4.2.2 Geomechanical Aspects of Well Integrity

The injection of CO_2 leads to stress changes and deformations in the injection zone, which may have an effect on the well integrity. Two possible issues due to changes in pressure regime are:

- Axial loading of the casing by reservoir decompaction
- Casing damage due to shear stresses at the reservoir-cap rock interface and at reservoir bounding faults.

4.2.2.1 Reservoir Decompaction during Injection

When CO_2 is injected, the formation pressure will increase, resulting in decompaction. This change in downhole pressure will induce additional stress on the wellbore. In the worst case, the formation will behave elastically, and will return to its original shape (before initial production).However, it is likely that only a fraction of the compaction that occurred during production will be reversed (Nagelhout, et al., 2009).If CO_2 is stored in a non-depleted formation, the increased pressure may cause the formation to be lifted up, which can lead to the formation of micro-annuli at the level of the storage formation and at cap rock level.

The vertical strains and stresses of the reservoir that are associated with the worst case CO_2 injection scenario are generally within the elastic deformation range of the casing. However, the elasticity modulus of steel is about 15 times higher than that of cement of the formation (IEA GHG, 2009). Thus, the stresses and strains induced as a result of decompaction will cause more deformation on the cement and the formation. This contrast in elastic material behaviour can lead to local failure of the bond. Debonding would lead to the creation of micro-annuli at the cement-casing interface (Mulders et al., 2007). This effect is more profound where most differential strains occur i.e. at the reservoir - cap rock level.

Furthermore, extensional stresses exceeding the tensile strength of the cement during the injection of CO_2 may create tensile fractures in the cement. As a result, both horizontal and vertical cracks may be formed along the cement-formation interface near the reservoir section. These cracks may provide additional leakage pathways for the injected CO_2, if interconnected.

4.2.2.2 Casing Shear

As a result of reservoir decompaction, shear strains and slip planes could develop between lithological layers with different stiffness and in places where existing discontinuities (e.g. faults) are present. The main area of interest for CO_2 injection is the interface between the reservoir and cap rock (Mulders et al., 2007).

With the use of finite element software strains in the reservoir, surrounding layers and discontinuities can be modelled and compared with the maximum allowable strains. A study by Philippacopoulos and Berndt (2001) suggests that an 8-12 cm lateral displacement could lead to a deformed casing. In practice, the displacement is in the millimetre region under foreseeable conditions and is therefore not a matter of major concern (Nagelhout, et al., 2009).

4.2.3 Corrosive Effects of CO_2 on Well Integrity

4.2.3.1 Cement Degradation

Although CO_2 itself is not corrosive, it forms corrosive carbonic acid when dissolved in water. Water sources in the wellbore can be connate water, free water in the cement or free water resulting from capillary condensation. Furthermore, supercritical CO_2, which is the commonly used state of CO_2during injection, hydrates rapidly by absorbing connate water.

Degradation begins when carbonic acid comes in contact with cement, and reacts to form calcium carbonate ($CaCO_3$). This stage is also known as carbonation. The resulting calcium carbonate creates a zone of denser and less porous cement. This zone will slow down the penetration of CO_2 further into the cement, and decrease the rate of degradation (Kutchko et al., 2007). However extensive carbonation can lead to the development of micro and macro cracks and to the loss of structural integrity (Carey, et al., 2007).

Continuous exposure to CO_2 will eventually start to dissolve calcium carbonate, resulting in the formation of channels within the carbonate zone and an overall increase in porosity (Barlet-Gouèdard et al., 2008; Duguid et al., 2007). Moreover, this reaction will also decrease the mechanical strength of the cement, and CO_2 will penetrate deeper into the matrix due to increased permeability.

4.2.3.2 Casing Corrosion

Carbonic acid is also reactive with well casing steel. As carbonic acid molecules contact the steel surface a cathodic reaction takes place during which hydrogen ions are released. These ions react with iron molecules of the casing to form an iron oxide film. Corrosion due to this oxide is an active form of corrosion. Its deteriorating effects may be reduced, but can continue after the oxide coating has formed.

The released hydrogen ions cause general corrosion or a localised attack on the metal surface resulting in pits, crevices, ringworm or guttering. The rate of corrosion depends on the temperature and partial CO_2 pressure. Under reservoir conditions, corrosion rates higher than 10mm/year for carbon steel have been reported (Brondel, et al., 1994).

5 Monitoring Techniques used in Well Operations

This chapter summarizes the methods for monitoring abandoned wells. The chapter is divided into a section about direct monitoring (Section 5.1) of an abandoned well (only possible after re-entering the well) and indirect monitoring (Section 5.2).A separate section is dedicated to so-called streaming potential measurements (Section 5.3). This technique was paid special attention in this work, because it might be an innovative technique to monitor well leakage and also because there is not much experience available up to now.

Any abandoned well that is relevant in the context of a safe CO_2 storage operation must have known coordinates. First of all, detailed documentation about the well is necessary. If the documentation does not suffice to locate the well accurately enough, a location method may be deployed. Several geophysics based techniques exist to locate wells. On-shore, the determination of the wellborelocation may be achieved by using electromagnetic induction techniques. Off-shore in saline water, these geophysical methods for locating wells might not work.

Three situations can occur:

- the well is detected and re-opened: the standard tools for accessible wells can be applied
- the well is found, but is not re-opened: indirect methods can be applied
- the well is not found, but its approximate location is known: only indirect methods can be applied.

Many things have already been thoroughly investigated, with regard to the application of indirect techniques for monitoring CO_2 leakages. The situation for abandoned wells is different from monitoring an entire reservoir complex in the sense that instead of monitoring a large area only the vicinity of the abandoned well needs to be considered in a first monitoring effort. Also potential migration pathways for the CO_2 may have to be considered, but most important is that a leak from the abandoned well itself can be detected. Once CO_2 leaks into the subsurface, the CO_2 may propagate along extended distances from the abandoned well. Therefore, when evaluating the risk of an abandoned well, the geological setting of the area around the abandoned well should be taken into consideration as well.

5.1 Direct Monitoring of the Well

Direct monitoring refers to the direct measurement of properties of the wellbore. They can only be applied if there is access to the wellbore.

5.1.1 Techniques for direct Monitoring

Below a list is provided with the monitoring methods/tools that can be used to assess and monitor the integrity of accessible wells (re-opened). The work will be finalized next year. A previous CATO-2 report (Kolenberg et al., 2012) describes in more detail the different logging tools for well inspection.

In this study only a very short summary is presented. The text in this chapter is an adapted version of Vandeweijer and Flach (2010), and includes a table as given by Kolenberg et al. (2012). The table presents a sort of checklist of various tools that can be used during the life of a well. Various tools in this list (Table 5.1) are able to give similar information; different approaches can therefore be valid for different wells.

The following well integrity logging tools are described in more detail:

1) Ultrasonic leak detector
2) Cement bond log
3) CET and CMT
4) Electromagnetic imaging tool
5) Multi-finger imaging tool
6) Down-hole video log
7) Gamma ray
8) Pressure sensors
9) Temperature sensors

Table 5.1.Logging tools for well integrity selection (modified after Kolenberg et al., 2012).“++”: primary method of logging; “+”: provide supplementary information; “-“: does not give any useful information; “--“: cannot be performed under specified conditions

Method	New well	Existing well	Operation	After abandonment
Ultrasonic leak detector	+	+	+	--
Downhole camera	+	+	+	--
Continuous temperature measurement	--	--	++	+/-
Multi-finger calliper	+	++	+	--
Electromagnetic thickness	+	++	+	--
Ultrasonic casing imager	+	+	+	--
CBL/VDL	++	++	++	--
CET/Ultrasonic imaging tool	+	+	+	--
Segmented bond tool	+	+	+	--
Borehole Audio Tracer Survey	+	+	+	-
Reservoir pressure monitoring	--	--	++	+

In the following sections, a description is provided of some of the individual monitoring tools including an assessment of the efficacy of the tools.

In terms of corrosion monitoring, new (quantitative) tools, e.g. Noise Surveys, are presently being developed. These novel techniques are beyond the scope of the present study, but has been/will be addressed in other CATO-2 WP3.4 deliverable (deliverablesD15 and D16).

5.1.1.1 Ultrasonic leak detector

Ultrasonic leak detectors can detect gas or fluid leak in the casing from the high-frequency noise associated with turbulent flow. The frequency spectrum produced by a leak is a function of differential pressure, leak magnitude and leak geometry. Ultrasonic leak detectors can pinpoint the exact location of the leak within the casing. Furthermore, these detectors are also sensitive to the leakage occurring in outer (secondary or tertiary) casing despite a drop in accuracy.

5.1.1.2 Cement Bond Log (CBL)

Sonic bond tools or cement bond tools transmit an acoustic 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. A log like this is of great importance in order to correctly assess the integrity of the well.

CBL measurements are usually combined with Variable Density Log (VDL) measurements to get a better understanding of the cement integrity. VDL measures the cement density, which gives information about the strength of the cement. CBL and VDL are run in combination to establish proper calibration which in turn leads to a better representation of the actual situation.

A significant disadvantage of CBL and other acoustic logging tools is that their use is only limited to fluid-filled wells. Acoustic waves cannot propagate efficiently through gas, resulting in inaccurate measurements in gas-filled wells.

5.1.1.3 CET and CMT

Cement evaluation (CET) and cement mapping (CMT) tools use many of the features of cement bond (CBL) logs, but add a new feature - a circumferential image representing the cement quality, or lack of it. The ultrasonic imaging (USI) tool, an offshoot of the open-hole acoustic image log, is the most recent version of this class.

The CET uses conventional sonic log principles, with measurements made parallel to the tool axis, with 6 or 8 segmented transmitter receiver sets spaced radial around the tool. CMT tools use an ultrasonic pulse echo system, measuring radially, again with 6 or 8 radially spaced transducers. USI type tools use a rotating head, pulse echo concept. The presence of a rotating head ensures that there are no gaps in the created image. USIT offers better lateral resolution than both CET and CMT. Similar to CBL, these measurements can only be performed accurately in fluid-filled wells.

5.1.1.4 Electromagnetic Imaging Tool

An electromagnetic imaging tool, like the EMIT, uses electromagnetic technology to measure and map the inner pipe diameter and the total thickness of all concentric pipes. The magnetic energy used by the EMIT is insensitive to most of the common minerals that precipitate in well bores. Therefore it is suited to image the pipe integrity through thick layers of scaling. The EMIT tool can be applied repeatedly in order to create a time-lapse series.

5.1.1.5 Multi-Finger Imaging Tools

Multi-finger imaging tools, like the Kinley Caliper and the Platform Multifinger Imaging Tool (PMIT), provide high resolution multiple internal tubing radii measurements using mechanical calipers, and generates a detailed image of the inside of the casing. In combination with electromagnetic imaging tools, multi-finger tools can be used to generate a complete internal and external image of the casing.

5.1.1.6 Downhole Video Camera

Downhole video cameras can be used to visually inspect the inside of the innermost casing for corrosion and leaks. The image quality is affected by the fluid in the well, and the best results are achieved in gas-filled wells due to clearer wellbore.

5.1.1.7 Gamma Ray

Together with the EMIT and PMIT tools a gamma ray can be run. This tool can provide data on the radioactive properties of material present in the well bore.

These measurements, although not directly linked to well integrity, can provide insight in the mineral composition of the scaling and the overall state of the inner tubing.

5.1.1.8 Downhole Sensors

Unlike logging tools which require the well to be open for the duration of data collection, downhole temperature and pressure sensors provide continuous data flow even when the well is closed. Naturally, the well still needs to be reopened to install the desired sensors since it is highly unlikely that a well at the end of its life is abandoned with sensors installed for permanent monitoring. The efficiency of using downhole sensors in abandoned wells is unknown. However its benefits could be investigated by placing sensors in re-opened abandoned or suspended wells in short term CCS projects.

Most of currently available downhole sensors use either electrical or optical fibre cables for power and data transfer. Quartz sensors/gauges are commonly used in electrical data transfer. These work as piezoelectric sensors and convert the changes in local properties to electrical charge which is then transferred to the surface. The measuring principle of optical fibre cables depend on the change in the scattering of light within the cable due to change in physical conditions. Conditions such as temperature, pressure and tensile forces induce oscillations on the fibre. These oscillations trigger a spectral shift on the scattered light. The change in conditions is determined from the spectral shift of the light scattered back from the fibre.

There are also a number of wireless sensors available in the industry even though their use is limited. Downhole sensors usually have a minimum life expectancy of 5 years under maximum pressure and temperature conditions, while some wireless sensors are certified up to 20-25 years (ICDP).

5.1.1.8.1 Pressure Sensors

Placing pressure sensors in a re-opened well for monitoring the downhole pressure can give information on the propagation of the carbon dioxide plume in the storage reservoir. When pressure anomalies are found these can be related to both reservoir characteristics and well integrity. Especially measured pressures below the expected values could raise concerns with regard to system integrity, since it can indicate leakage through surrounding formations or through the re-opened abandoned well. A potential disadvantage of the installation of a permanent cable is that a possible leak path along that cable is formed.

5.1.1.8.2 Temperature Sensors

Placing temperature sensors in a re-opened well for monitoring the downhole temperature can give information on the flow of the carbon dioxide. Anomalies from the normal temperature can indicate an increase in fluid/CO_2 transport. Therefore downhole temperature measurements can be used to find leaks. A potential disadvantage of the installation of a permanent fibre-optic or other line is the creation of a possible leak path along the line.

In addition to conventional sensors which allow measurements at specified points, temperature measurements can also be performed along a continuous profile. This type of measurement is called Distributed temperature sensing (DTS). In DTS systems, temperature is measured along the length of the optical fibre cable, resulting in a real-time temperature profile along the length of cable. These systems are commonly used in permanent downhole monitoring in fields where thermal methods are applied as means of enhanced oil recovery.

5.2 Indirect Methods

Indirect methods concern those methods that do not measure the well itself, as it is inaccessible, but any leakage occurring from the well. These include geophysical methods and other leakage or techniques for CO_2 detection. The leakage may occur over the entire depth range of the well.

When CO_2 comes out of an abandoned well, first it will dissolve into the groundwater. When the water is not so mobile however, the saturation level will be quickly reached and CO_2 will mostly remain, depending on its depth, in a gaseous state. At some stage in the leakage process CO_2 may come to the surface.

5.2.1 Geophysical Methods (including Cross-Well Measurements)

Many geophysical techniques exist of which only a few are relevant for monitoring leakage from abandoned wells. Only the techniques that may be relevant are mentioned here.

For a specific CO_2 storage project in which abandoned wells may be an item, a site-specific monitoring scheme must be designed. Here, a priority list of relevant techniques to be considered is given. The list can then be used by considering initially the first technique and consider its applicability for the site and then the next, etc.

First, the methods are described below. This is followed by the priority list at the end.

Each method can be employed from the surface only, or partly (well to surface) or entirely from wells (cross-well configuration).

5.2.1.1 Repeated Seismic Reflection (2D/3D)

3D surface seismic reflection surveying has a good spatial coverage but is relatively expensive, especially on land. It is probably the most sensitive technique to detect any leakage as it is sensitive to any gas phase in the subsurface. It also has a relative good resolution. Because of the costs it is not expected that conventional surface repeated active 3D seismic surveys will be used to monitor abandoned wells.

An example of monitoring a well from which gas is escaping using seismic reflection surveying is given by Landrø (2011).

However, the installation of a permanent buried receiver network in the area where the abandoned wells is located can be proposed. Then a seismic source can be applied in regular intervals to gather necessary data. With this setup, each survey will require less than a week of field work.

Experience in Ketzin (Arts et al., 2012) shows that burial of the receiver network improves data quality and repeatability. A depth of about 10 – 15 m may be sufficient for good data quality.

5.2.1.2 Repeated Electromagnetic Surveying

Electrical and electromagnetic monitoring, repeated in time, measures the change in resistivity due to CO_2 injection. The resistivity is expected to increase when CO_2 replaces conductive formation fluid, such as brine. Because the spatial resolution is not so high, the sensitivity of these methods is also relatively low. However, monitoring implies observing differences and can increase the sensitivity of these methods relative to “mapping”. Still, it will probably be hard to tell at which depth the leakage occurs. A well-to-surface application does improve the vertical resolution and sensitivity.

5.2.1.3 Self-Potential

Streaming potentials originate when an electrolyte is driven by a pressure gradient through a porous medium with charged walls. Therefore, streaming potentials may be used to detect a leakage from an abandoned well (or any other leakage) that causes groundwater flow. Streaming potentials are known in the field of geophysics, but are not generally and widely applied.

Within this CATO-II work program work was done to evaluate the applicability of SP for detecting leakages of CO2. This work is reported in Appendix A. The main conclusions are given here.

Modeling indicates that recording streaming potentials can be a useful technique to detect leakages from abandoned wells (or other leakages). The main limitation of the method is the amplitude of the SP-signal for realistic conditions. For relative shallow leakages the technique is more sensitive because the distance to the source of the signal decreases and because the volume of displaced water from a leakage increases.
Most field experience exists with relative straightforward 2D-like acquisition geometries for shallow applications. It is expected that the combination of multi-channel recording and processing techniques will push the limit of the lowest detectable signal significantly, thus increasing the depth from which a leakage can be detected and thus increasing the applicability of the technique. This requires further research. This research could be done already in combination with some field test, as the basic principles are not complex and adequately understood.

Measurements in a tank in the laboratory show that streaming potentials related to injection can be measured. The signal is not stable though and the spatial (lateral) pattern of the amplitudes shows quite some noise.

5.2.1.4 Microseismicity Monitoring

Microseismic monitoring is applied by positioning permanent seismic receivers in a well or in a buried grid below the surface. Often, the aim is to monitor fracturing induced by increase in pressure as a result of the leakage by measuring the acoustic signals produced by the fracturing process. By recording all seismic events, the spread of injected CO_2 might become visible .It is assumed that the CO_2 front aligns with seismic events. The success of the method depends on the occurrence of recordable seismic events, which is expected to be low for leakage from abandoned wells.

As a leakage may occur with and without seismic events, the method is not considered appropriate for monitoring abandoned wells. However, when a grid of seismic receivers is placed for repeated seismic reflection surveying, this grid of receivers can be used to monitor any other seismic events for a relatively low cost as the hardware is there. However, the recording and processing of continuous seismic data is not an easy task.

5.2.1.5 Gravity applied at Surface or in the Well

It is not expected that gravity measurements conducted from the surface or from a borehole is useful for monitoring leakage from abandoned wells, as the sensitivity is too low. Only by carrying out a base-line survey and then repeated surveys, gravity might detect changes in the subsurface due to shallow gas accumulations.

5.2.1.6 Cross-Well Employment

In cross-well technology, sources and receivers are placed in one well and measurements are done in also at least one other well. To design a setup for monitoring leakage from abandoned wells, at least three new wells, preferably four, have to be drilled.

For a geophysical technique to be effective as a cross-well method, the wells have to be drilled down to about the depth of the leakage. However, this depth is not known of course, so that relative deep wells have to be drilled.

Due to the amount of additional cost related to the drilling of multiple new wells, cross-well technology is not considered to be a suitable method for monitoring leakage from abandoned wells.

5.2.1.7 Well to Surface Employment

In well to surface techniques only one well is needed to be drilled to place either a source or receivers and is thus cheaper than cross-well methods. Other sources and receivers can be placed at the surface. For well-to-surface measurements the advantage over surface application is that the spatial resolution increases for both reflection methods (seismic) and potential measurements (electrical and electromagnetic).

For seismic measurements this configuration is often called Offset Vertical Seismic Profile (VSP). The spatial coverage using one well to surface is better than it is for cross-well tomography.

5.2.1.8 Priority List Geophysical Monitoring

This section intends to present a way to decide which geophysical technique may be applied for detecting a leakage from an abandoned well. As indicated already, a geophysical technique may be relevant once it is decided that there are abandoned wells on a CO_2 storage location for which it was decided not to re-open them (because the risk is low and it is economically unfeasible), but for which monitoring any leakage is considered useful. For this, also an estimate of most probable depth of a leakage should be determined.

The most sensitive method for most leakage depths (more than 200 m) is repeated seismic reflection. Offshore, this can be realized by repeated full acquisition (sources and receivers). Onshore, a grid of geophones can be implemented that may be buried to a certain depth (e.g. 10 – 20 m). A source is applied as often as is deemed necessary for the abandoned well.

If seismic reflection is considered not useful or too expensive, SP may be an alternative on land. The applicability of SP must be evaluated by carrying out a modeling study using a finite differences model or something similar, of the subsurface. Especially for shallow leakages SP may be relevant, since seismic reflection becomes less effective for shallow depths.

If monitoring of potential shallow leakages is required, the placement of sensors in the groundwater or above is a possibility.

5.2.2 Methods at the Surface

The detection of leaking CO_2 near abandoned wells can be done above ground, in the vadose zone or at some depth below the water table.

Above ground measurement techniques include covariance towers, flux chambers and isotope analysis. However, it is difficult to discern a small CO_2 loss from natural variations, and hence assessing a sound baseline survey is important.

Changes in bio-communities can be used to detect CO_2 leakage indirectly.

NETL (2009) discusses the use of laser light for monitoring larger areas: “Sensors for detecting and monitoring CO_2 in the air are a widely deployed technology (greenhouses, combustion emissions measurement, and breweries), but are mostly used for point sources of CO_2 and operate as infrared gas analyzers (IRGA). When monitoring a large area (several km^2 in area), one solution is to employ an open-path device that uses a laser that shines a beam (with a wavelength that is absorbed by CO_2) over many meters. The attenuated beam reflects from a mirror and returns to the instrument for determination of the CO_2 concentration.

An example of a sensor to use at depth is the HydroC™ CO_2 sensor (CONTROS Systems & Solutions GmbH). Dissolved carbon dioxide diffuses quickly from the liquid through a patented thin film composite membrane into the internal gas circuit. Here the CO_2 concentration is measured with high accuracy by non-dispersive infrared sensors (NDIR).

Currently extended research activity is being conducted regarding the detection of CO_2 at the surface, e.g. the EU projects: RISCS (onshore), ECO2 (Offshore). Also within CATO-2 relevant work is being performed, e.g. in WP3.9, with the development of fibre-optic CO_2 sensors. For further details please refer to the respective projects.

5.2.3 Methods at the Sea-Bottom

For the detection of CO_2 coming out of the sea-bottom near abandoned wells, some specific techniques are emerging that may be deployed at relatively low costs. They aim at measuring CO_2 fluxes and precursory fluids at the sea bottom and require a good knowledge of the baseline situation.

Measurement techniques include (Wright, 2012):

- physical techniques for bubble detection that can be either passive hydrophones or active sonar recordings
- chemical techniques including elevated salinity, manganese, acidity, Iron(II) and lower dissolved oxygen
- monitoring biological communities by looking at faunal community composition, presence of key indicator species and behavioral responses.

5.2.4 Other Indirect Methods

If the well is found, but not re-opened, it may be an option to place vibration sensors somewhere on the well. It happens that when a leakage occurs, the pipes in the well start to vibrate (just like a tire that loses air). It may be a cheap option for a specific situation and can be considered in a measurement program for abandoned wells.

6 Well Remediation

The EU Directive on geological storage of carbon dioxide (EC, 2009) demands corrective measures to be taken when a leakage or significant irregularities are detected. Depending on the nature and location of the leak, remediation on an abandoned well may be the necessary. Furthermore, wells with high leakage potentials in a selected field may also be subject to remedial action prior to the start of operation, i.e. before CO_2 injection commences.

In case the integrity of a well is diminished during the storage operation or a high risk well has been detected in the site characterization phase, remediation of a previously abandoned well may be necessary to ensure the containment of CO_2. Usually, all well leakage scenarios are routinely considered in the site characterization phase and safeguards should be in place if the high risk well was not re-abandoned prior to the start of operation, i.e. before CO_2 injection commences.

Remedial actions can have any of the three following functions (IPCC, 2005):

- Controlling the rate of leakage by changing downstream pressures. Injection and reservoir pressures might be decreased to reduce the driving force of the leakage. Moreover, stopping injection and waiting for the field to stabilize will eventually lead to the elimination of leakage.
- Dispersing the CO_2 level in the area to harmless levels. Numerous different methods are available to decrease CO_2 levels in the event of a leakage. Common groundwater and soil remediation techniques such as extraction followed by venting or reinjection are used.
- Eliminating leakage through existing wells by means of repairs and re-abandonment.

Only the latter function is addressed in this study. Previous studies indicate that leakage through previously abandoned wells is the biggest integrity risk of a CO_2 storage project. It is estimated that any leakage observed in a CCS project will be a very slow process except leakage through improperly sealed abandoned wells (IEA Greenhouse Gas R&D Programme, 2008). Therefore, abandoned wells are considered to be the subject of most remedial work that will be required for proper CO_2 underground storage.

The remediation options for abandoned wells consist of re-accessing the well, stopping the leak and re-abandonment. The initial issue that rises is locating the well in question. Section 6.1 focuses on this topic. Re-entering the well will be discussed in 6.2, and available remediation/re-abandonment methods will be summarized in 6.3. Remediation of abandoned wells is a time-consuming, technically challenging and costly task. The additional costs resulting from remedial work will be discussed in 6.4.

6.1 Locating Abandoned Wells

To successfully monitor and remediate any existing wells, their locations should be known. Data about well trajectory is also important for accurate monitoring. A properly abandoned well will not show any direct signs of its existence on the surface, as the wellhead would be removed, and the casing at surface would be cut at a certain level below the surface. Furthermore, the well location may not be accessible from the ground due to vegetation or urbanization. Excavating without data is careless, and will not give any information on the trajectory even when successful. Any wells in the area should first be located from existing records or using wide-scale surveys. To pinpoint the trajectory of the well, geophysical survey methods are needed.

6.1.1 Well Records

Currently, a number of states have established (or are establishing) a database of wells records that are available online. These databases contain basic information about all recorded wells such as location and depth, as well as detailed well logs and deviation surveys. Assuming that all activity has been accurately recorded; all the necessary information needed to locate existing wells in an area can be gathered from these databases.

Such a well record database also exists in the Netherlands, and is maintained by TNO. Basic information on any of the wells that have been drilled can be reached immediately, with detailed data available after five years. Nevertheless, the quality of the well database might not be as high everywhere. The database may not be complete or updated regularly in some places. Unrecorded wells may be present in large areas with high drilling activity or in places with sub-standard regulations. Moreover, wells that have been drilled and abandoned long before any database or regulations were established might exist in locations with a long history of drilling. To overcome any issues that may arise due to the lack of existing data, surveys are also needed.

6.1.2 Wide-Scale Surveys

Wide-area surveys are conducted to gather information about the whole area of interest. Depending on the method, these surveys can give indirect or direct indication of previous drilling activity in the area.

6.1.2.1 Indirect Surveys

Indirect wide-area surveys comprise aerial photography and remote sensing. These methods cannot locate any trace of a well below surface, but rather aim to indicate probable areas of previous well activity from noticeable differences compared to the surroundings. A common indicator of an existing well is an area of decreased vegetation in heavily vegetated areas (Jordan & Hare, 2002).

Any results from indirect surveys will be inconclusive, if there is no additional data available to support the findings. Discrepancies in imagery could result from a number of different reasons other than well activity. Therefore, these methods are better suited for locating sites that contain indication of activity above surface.

6.1.2.2 Direct Surveys (Wide-Scale Geophysical Surveys)

Geophysical surveys target abnormalities of certain physical parameters in the sub-surface. In the case of an abandoned well, the primary targets are steel casing and cement. Wide-scale geophysical surveys include low-altitude airborne measurement methods which provide very fast data acquisition at low-moderate costs.

Available wide-area methods for locating abandoned wells are airborne magnetic and electromagnetic surveys. Both of these methods are only useful at detecting steel casing, and cannot locate cement plugs. Because steel has high magnetic permeability and electrical conductivity, it is an excellent target for such surveys. With continuous improvements and increased resolution airborne surveys can pinpoint the location of the well casing to within a few meters.

The main disadvantages of airborne geophysical methods are limited depth of investigation and industrial noise. Currently, airborne surveys can only penetrate a few hundred meters into the subsurface. This depth is enough to locate the top of casing, but will not give any indication to the trajectory. The penetration depth is further limited in the presence of a magnetic/conductive near-surface formation (Jordan & Hare, 2002).

6.1.3 Ground Level Surveys

If the area of interest is small (a few km^2), airborne surveys may be deemed costly. An alternative in such cases is to conduct ground level geophysical surveys to locate abandoned wells. Furthermore, surveys on ground level may provide higher resolution and penetration depth. Available ground level methods that can be applied to detect casing and cement are ground level magnetic/electromagnetic surveys and Ground Penetrating Radar (GPR) surveys.

Ground level magnetic and electromagnetic surveys follow the same principle as their airborne counterparts. The surveys are usually carried out on foot using certain devices. Data acquisition is quite fast compared to other common geophysical survey methods.

6.1.3.1 Ground Penetrating Radar

Ground penetrating radar is essentially a very high-frequency electromagnetic surveying method which makes use of radar pulses to image the subsurface. In this method, radio waves are transmitted into the subsurface, and variations in dielectric constant are mapped from reflection of these waves.

GPR surveys can detect discontinuities in the subsurface, and offer significantly higher resolutions compared to other ground level surveys. Because the method is sensitive to the dielectric constant of material, cement plugs at the top of the well can also be detected using GPR.

As the method uses very high frequency waves, the depth of penetration in GPR is fairly limited. Under most conditions, surveys can only gather information from up to several meters of depth. Furthermore, this method is less cost-effective and provides slower data acquisition than other available methods. Therefore, this method will be effective for wells that are known to exist, but need to be located. In locations where the soil is highly conductive, this method is unlikely to detect the surface casing or the surface plug as the detection depth limit will be significantly reduced.

6.2 Re-entering Abandoned Wells

After the well has been located, accessing the wellbore will be required to perform any remedial work. A drilling rig is required to re-enter the well. The rig will be placed above the location of the well, and drilling will commence initially to connect with the abandoned casing string. To provide a secure connection with the old casing, casing swages and overshots should be used.

Once the casing has been reached, the cement plug at the surface will be drilled out to gain access to the wellbore. Any other plugs that prevent passage to the location of the leak also have to be drilled out before remedial actions can take place. In combination with the mobilization of all equipment and personnel, any drilling performed for remediation will be a time consuming and costly practice.

In the case that the well is not accessible from the surface, a remedial well that provides access from the casing should be drilled. Remediation under these conditions will introduce additional costs. Furthermore, with the addition of another trajectory a new potential leak path is introduced to the system. Any problems that may occur from this can be minimised by applying CO_2 resistant industry best practices in the new hole.

6.3 Remediation Methods

Different remediation options are available depending on the location of the leak. If the leak is through the casing string or outside the string, the well needs to be killed first by pumping a heavy fluid (usually mud or cement) through the annulus. Remediation is then carried out by perforating the casing at the location of the leak and injecting cement through these perforations. This operation is known as the cement squeeze method. Alternatively, casing patches may be used when the leak is through the casing. However, patches usually provide short to medium-term integrity; thus should not ideally be used in an operation that aims to provide long-term integrity such as the case in CCS.

If one of the cement plugs has been degraded and CO_2 escapes within the wellbore, the plug should be drilled out, and replaced according to industry best practice. In their recent study, SINTEF recommends using fullbore formation (or pancake) plugs in CO_2 environments where the cement or casing is suspected to come in contact with CO_2 (Randhol & Cerasi, 2009). This method can also be used for leaks through or outside the casing string, after the well has been killed. Regardless of the location and the mode of leak, any plugs that have been drilled out to re-enter the well should be replaced at the end of remediation according to most recent regulations.

6.3.1 Cement Squeeze Method

In most cases, leaks behind the casing indicate problem in the integrity of the cement sheath. To determine the presence and location of leaks in the annular space, logging will be necessary. Several methods mentioned in the previous chapter may be used for this purpose. Pinpointing the location and extent of the leak is important for perforation design and the amount of material necessary.

In the cement squeeze method, the cement is forced through the perforations by pressure. As the cement slurry encounters a formation, the solid particles are left behind while the liquid penetrates through the formation matrix and covers the porous space within the rock. The cement will also fill any voids present in the cement sheath, and will work to re-establish the integrity of the annular space.

The cement used in cement squeezing should have certain properties to be effective. The viscosity should be low to allow passage through perforations and other small spaces, so that the slurry can reach the void that needs to be filled. It also needs to have low fluid-loss characteristics to prevent setting of the slurry before it reaches its intended destination.

Potential problems for cement squeeze method include reduced integrity of the casing by the presence of perforations and uncertainties surrounding the actual placement of the squeezed cement in the annulus. Milling part of the casing, and installing cemented expendable casing instead may reduce risks, but still does not guarantee fully restored integrity.

6.3.2 Fullbore Formation (Pancake) Plug

Detailed information on fullbore formation plugs (FFP) will be available as part of deliverable D10 in CATO-2,WP3.4. The present text will therefore only briefly discuss properties and operations regarding FFPs.

The setting of FFP starts with the installation of a mechanical barrier/cement retained at the bottom of the interval to be filled. Then the casing and the primary cement sheath around the location of the leak is milled away. It is essential that milling continues for a while into the formation to ensure that the entire cement sheath in the interval is removed. After milling, all the swarf is removed and cement is filled in the cavity to establish a proper well barrier. The quality of the placement and integrity of the plug is confirmed by the same tests that confirm the integrity of a regular cement plug (Section 4.1.2.1).

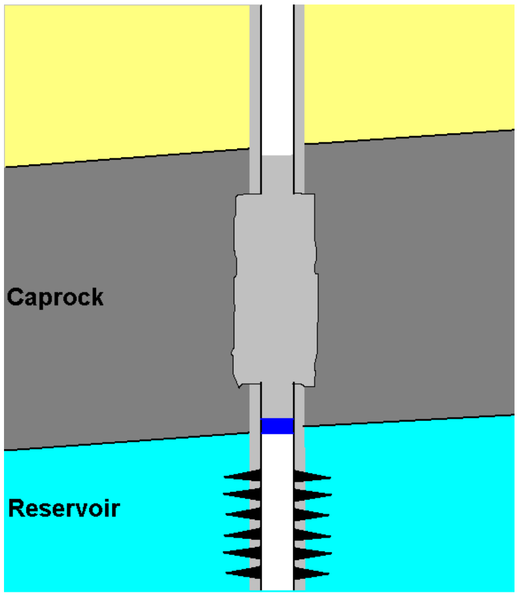

Figure 6.1. Typical cross-section of an FFP plug (Nagelhout, et al., 2009)

A properly placed FFP will re-establish the integrity of the abandoned well. Furthermore, an FFP will remove three potential leak paths; the corrosion sensitive steel casing and the steel-cement interface both inside and outside the string. If the configuration of the well allows, it is suggested to use a CO_2 resistant cement type in the plug to further enhance well integrity. However, the compatibility of the cement in the plug and the completion cement should be confirmed beforehand. If the cement types are incompatible with each other, well integrity cannot be ensured from the resulting remediation.

6.4 Costs of Remediation

Any remedial operation on abandoned wells is expensive. Unfortunately, no detailed study about remediation costs in a CCS project has been made so far. In reports by IPCC (2005) and IEA (2007), the cost of locating abandoned wells has been estimated to cost $100,000/survey while plugging costs have been estimated at $50,000 – $100,000. However, these estimates for plugging are rather conservative and cover only the material costs. Most of the costs for any remedial operation on an abandoned well will be related to the rental of drilling rig and services. The cost also depends on conditions such as the depth of the leak and the abandonment configuration of the well as this will affect the duration of the operation. Naturally, a longer operation would result in higher costs. It is estimated that at the current rates, remediation costs for a single onshore well with a simple well geometry (e.g. open-hole) may be around € 1 Million and could add up to a few million Euros for a delicate remediation operation. If the target well is located offshore, the estimated cost can easily escalate to €5-10 million depending on well construction, site specific aspects and the complexity of the remediation activity.

7 Monitoring Strategy

In this chapter, a general monitoring strategy for abandoned wells is proposed. The aim of the monitoring strategy is to detect and analyse any integrity issues that may rise during the project as soon as possible and mitigate the problems if necessary. As every candidate field and well is unique, it is unlikely to propose a strategy that covers all possible outcomes. Therefore, only a general workflow for a generic field with emphasis on potentially useful methods is presented here. It should be noted that while abandoned wells are a part of the monitoring strategy of a CO_2 storage project, only the strategy regarding abandoned wells is discussed here.

The monitoring strategy could be split into three parts of the project: before injection, during injection and after injection. A flow chart summarizing the suggested monitoring strategy is displayed at the end of the chapter (Figure 7.1).

7.1 Monitoring before injection

7.1.1 Well Database and Selection

The monitoring strategy should start with a detailed risk assessment study of the field in which any potential leak points in the system are detected, if applicable including acquiring baseline data.. Establishing an accurate and complete well database is the first step of the monitoring strategy. This database should include information on completion (both casing and cement), plugging and abandonment practices performed on the wells. Database establishment should also be a significant part of the site selection process. Selecting a site with less leakage potential would be economically and environmentally more feasible. Moreover, it would better fit the goal of permanent carbon dioxide containment (see the EC Storage Directive).

Ideally, every single abandoned well should be located and all data should be obtained from existing well records. Moreover, a wide-scale, airborne geophysical survey would be useful to confirm the presence of wells, and to locate any wells that are missing from the records. However an airborne survey might be considered economically unfeasible, especially for small locations. For offshore locations, electromagnetic or magnetic surveys to map the seafloor will be necessary to locate abandoned wells. If information about trajectory, completion and abandonment of a well is missing or lacking, it should be considered as a risk for CO_2 containment, and therefore a target for monitoring. Actually the presence of such wells in a candidate field may result in the refusal of the field as a storage site in the first place.

After all existing abandoned wells on the field have been determined; the wells that require monitoring should be established. Apart from high-risk wells, which are identified either from available (or lack of) data, all wells penetrating the target reservoir/aquifer or the cap rock need to be monitored during the life-cycle of the CO_2 storage operation until the responsibility of the site is transferred to the competent authority.

7.1.2 Pre-operation Tasks

Pre-operation tasks include any remedial work that can be performed prior to injection and the installation of the monitoring network.

7.1.2.1 Remediation

Even though remediation can be performed during any phase of the project, it does not automatically guarantee a leak-proof well, but minimizes the risk of leakage. As mentioned in the previous chapter, any remedial work performed on an abandoned wells will be a costly and time consuming operation, thus will be avoided under most circumstances. However, a situation may arise in which remediating an abandoned well before the start of injection would be more advantageous instead of continuing the project with a high risk of leakage (including the risk of growing public resistance). The decision to re-abandon (all) existing wells penetrating the storage compartment would become more likely when the injection target is a deep saline aquifer, where reservoir management and monitoring is proven to be more difficult due to dispersion of CO_2. Additionally the number of wells penetrating the formation is usually less than that in a depleted hydrocarbon reservoir. Large aquifers with oil and gas in local structures or aquifers with oil and gas below, present special cases. The second case could be high risk because an abandoned well was usually not abandoned with CO_2 storage in mind for the particular layer.

When a well is opened for remediation, direct monitoring methods could be implemented in the well to confirm integrity through the rest of the well. Most of these methods (logs, downhole camera, etc.) will only provide information as long the well is open, and will be used to locate the leak as well as assessing the integrity throughout the rest of the well.

Furthermore, permanent downhole sensors could be installed in the well to enhance the monitoring network and provide a continuous data flow. The possibility of installing downhole sensors should be carefully assessed, as the data cables running from the sensor to the surface will introduce new leak paths to the system if not properly sealed. To avoid inducing the possibility of a leak directly from the reservoir, the sensors should ideally be placed on above the primary or secondary cement plug. Installing DTS systems rather than conventional discrete sensors can also prove to be useful, as it will provide additional data on how the leaking gas moves within the well and the subsequent cement plug(s). Wireless sensor systems are also available, but have not been widely used in the industry.

The major drawback of downhole sensors is their limited life expectancy compared to the duration of a CO_2 storage operation. Most sensors are certified only for 5-10 years of operation, which means several partial re-entries to the well will be required in order to maintain continuous monitoring. This will introduce significant extra cost to the project. On the other hand, in recent years Schlumberger has developed a DTS technology that allows the fibre to be replaced offline to rig activities (Schlumberger, 2008). This and any similar technology would make DTS systems a feasible way of monitoring abandoned wells.

7.1.2.2 Monitoring Network for Abandoned Wells

With all potential leak paths defined, adequate methods to monitor the abandoned wells can be selected. As mentioned in Chapter 5, this network will comprise a combination of geophysical methods to determine leakage at deeper points and various sensors and geochemical measurements to determine near-surface leaks. The network should target all abandoned wells that penetrate the cap rock/storage formation of the storage compartment as well as any (accessible) high risk wells determined during the site characterization phase.

The specific methods to be applied will vary from site to site, and may even vary between wells within the same site. For instance, the SP method cannot be applied in offshore locations, and well-to-surface measurements that are usually considered economically unfeasible may prove to be invaluable in the presence of a cluster of abandoned wells. Therefore, while general guidelines are present, the chosen monitoring network is highly site-specific.

After specific methods have been selected, preceding surveys should be performed to establish baseline values. As most methods (especially geophysical) indicate a change in parameters, these initial surveys are essential for accurate monitoring of CO_2 storage sites.

7.2 Monitoring during Injection

7.2.1 General Strategy

The proposed monitoring strategy during injection comprises the following elements:

- Surveys must be taken frequently and on a regular basis throughout the injection period. A regular repetition of surveys ensures that the effects of injection are determined, and any anomaly indicating leakage will be detected at an early stage. Depending on the cost and the necessity of surveys in terms of storage safety and the injection, repeated measurements from a few per year to once every few years may be acceptable. On the other hand, sensors provide continuous data acquisition, and will detect any leaks within range as soon as it reaches surface/air.
- The monitoring network should be adaptive and progressive to be able to react to possible changes during injection. In order to achieve this, the monitoring efforts must be coupled with reservoir and injection modelling studies, conducted during the injection period. For a site where the propagation of the CO_2 plume is monitored; a scheme could be applicable, in which the storage compartment (hence, the abandoned wells) is monitored for a certain period, depending on the location of the plume and the wellbores. This approach would be more efficient and cost-effective than monitoring all the wells from beginning of injection, as the number of wells to be monitored regularly will gradually increase. Certainly, initial surveys will still cover the whole site. Note that for some storage reservoirs, e.g. with overlying evaporitic cap rocks, the application of this method is not suitable.
- The whole monitoring network of the project should be utilized to render timely leakage detection possible. The network for abandoned wells constitutes only a part of the monitoring efforts in a CCS project. Information gathered from injection wells, such as lack of increase (or inadequate increase) of downhole pressure can indicate a leakage of storage site. Even though its location cannot be pinpointed by these measurements, aligning this information with the data set of the monitoring network around abandoned wells may identify the exact leakage location –whether it occurs at a well or not and at which well. Another method that could be useful is time-lapse seismic surveys (if applicable, see above), covering the whole injection site and surroundings, provided that these surveys are considered essential for storage safety and are included in the monitoring plan of the project.

7.2.2 Leak Detection and Mitigation

When a leak has been detected during injection, studies and surveys will be conducted to detect the location and extent of the leak, and countermeasures (usually in place) are taken. If a well leak is detected near-surface, pinpointing the location and the source of leak will not be a hard task as readings in sensors would give a clear indication on the flow of CO_2 and the leak source. Detection of a leak that is deeper in the subsurface may not be that straightforward, as resolution limitations and wide coverage makes it more difficult to locate the leak. Furthermore, a leak occurring at depth may migrate to long distances away from the well, given the geological setting allows it. Even though this kind of leak is usually associated with cap rock and seal integrity issues, certain settings (e.g. abandoned wells penetrating faults) might allow CO_2 leaking from an abandoned well to be detected in an entirely different location.

The discovery of a leak in an abandoned well will not always necessitate well remediation. Decision for well remediation will only be made after the analysis shows that it is the necessary corrective measure to be taken or it is enforced by the competent authority. Even when the leakage rates are relatively high, remediation of deep leaks may not be needed in cases where the geological setting will trap the leaking fluid due to natural trapping mechanism (e.g. secondary cap rock/stratigraphic traps) so that the leakage out of the storage compartment is prevented. For leaks affecting the shallow subsurface, required mitigation could succeed with alternative remediation settings; such as decreasing injection rates to decrease the rate or even stop the leakage, groundwater treatment, soil remediation and re-injecting/utilizing the leaking CO_2; may provide more practical solutions.

Regardless of the progress and incidents during the injection process, monitoring should continue as planned throughout this period. Enhancements or modifications to the monitoring strategy can also be implemented, if deemed necessary.

7.3 Monitoring after Injection

Since the aim of CCS projects is to provide long-term storage, monitoring should confirm that long-term integrity has been established. Therefore, monitoring efforts should continue after injection has been stopped.

Initial studies suggested that monitoring should be continued for up to 10,000 years to ensure long-term integrity has been provided. However, trying to implement such a long monitoring scheme will be essentially impracticable. Furthermore, more recent studies suggest that the stored CO_2 will become more secure over time, since the formation pressure that drives the leakage process will start to decrease once injection is stopped (Chalaturnyk & Gunter, 2004; Senior, Espire, & Christopher, 2005). Another reason to expect decreasing leak potential is the fact that the injected mobile CO_2 will diminish as it dissolves in formation fluid or it is trapped in pore spaces or due to mineral reactions.

In a realistic approach, it is suggested to carry out monitoring efforts until the pressure and the CO_2 plume propagation in the target formation stabilizes. However, while the diminishing pressure decreases the potential of cap rock / seal integrity issues, problems with well integrity such as corrosion and degradation may occur as long as free CO_2 exists in the system. The actual time scale in which stabilization of the site is observed will vary, depending on the field structure and project specifications. In addition to accurate simulations, the entire monitoring network and probably additional methods will be required to determine the time at which the pressure stabilizes. During this period, monitoring of abandoned wells can continue by taking surveys on the surface, and repeating every few years.
After the absence of leakage and the stabilization of the site are confirmed, monitoring will not be required except under the suspicion of a leak or due to legal disputes. These issues and future actions (if applicable) will be discussed before the site is transferred from the operator to the competent authorities.

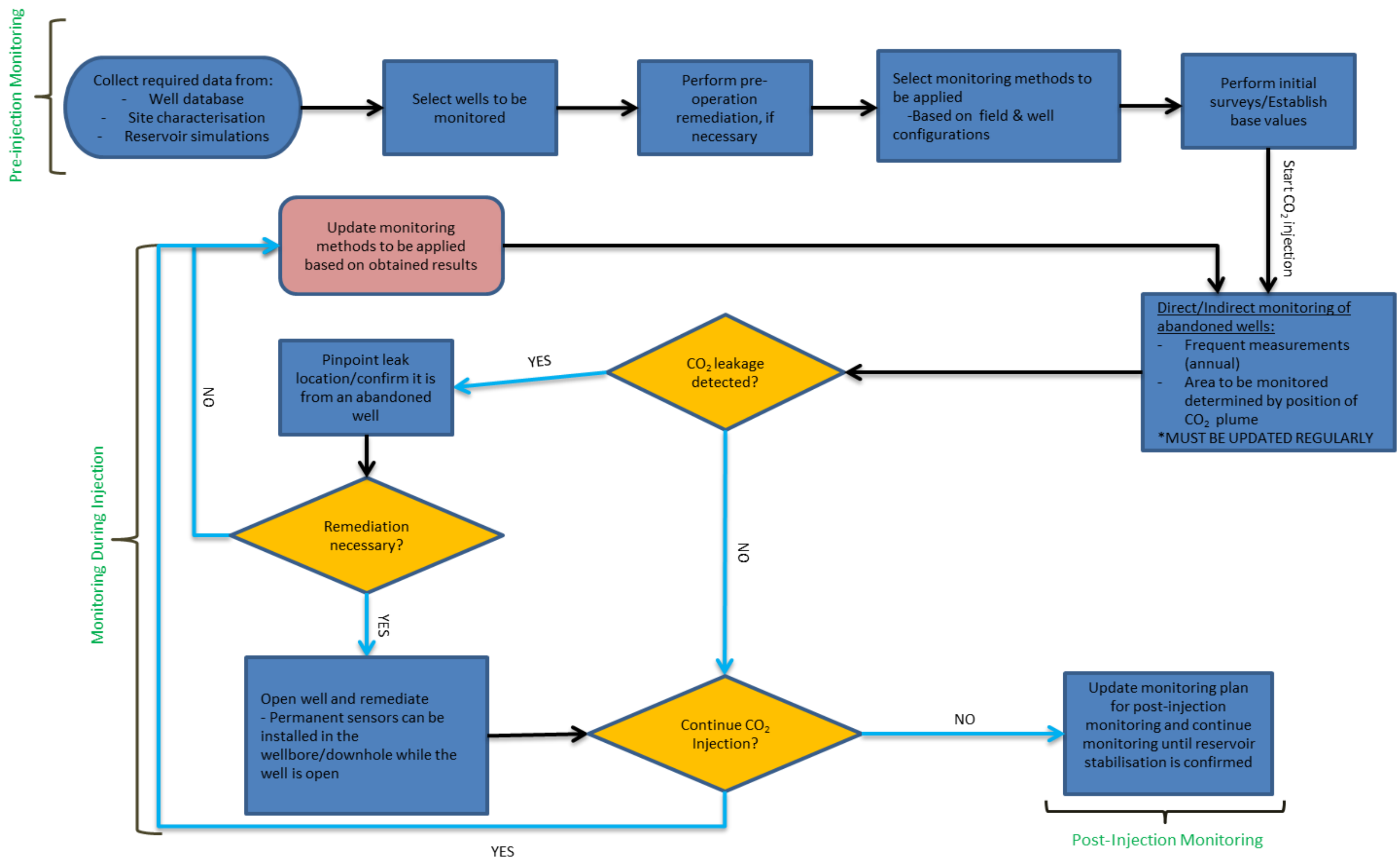

Figure 7.1. Suggested general monitoring strategy for inaccessible/abandoned wells in a CCS project

8 Conclusions and Recommendations

Leakage along or out of previously abandoned wells is considered as the biggest integrity risk for CO_2 storage operations. The main risks associated with previously abandoned wells are lack of detailed well data and poorly performed abandonment operations often related to insufficient regulation and technical standards at the time of abandonment. During abandonment, various issues can lead to the formation of leak paths within the wellbore or in the annuli. The changed pressure regimes and the corrosion potential due to the injection of CO_2 also can lead to additional integrity issues of previously abandoned wells. These potential risks make previously abandoned wells an important target for monitoring before, during and after the injection phase.

As CO_2 storage has become a major research topic in recent years, and many pilot studies have been conducted, well construction and abandonment regulations are presently being adapted to consider the entire life-time of a well, including the potential subsequent storage of CO_2 in the field. Unfortunately, these modifications do not affect the quality of previously abandoned wells. Therefore, the integrity assessment of these old wells is crucial for any future CO_2 storage site characterization.

A detailed characterization and identification of all possible leak paths is essential for monitoring abandoned wells. Only with the determination of all the risks, a satisfactory monitoring strategy can be implemented. Any lack of relevant data can result in a high risk ranking of that particular well if its (long-term) performance is uncertain. Since remediation options for abandoned wells are often technically challenging and very costly, a potential CO_2 storage field with a large number of "high-risk" wells is more likely to be labeled as unsuitable for storage.

The monitoring strategy of a CO_2 storage operation needs to be site specific due to various parameters that influence monitoring specifications (geology, injection parameters, size of the storage site, number of wells, applicable monitoring methods, etc.). Monitoring of abandoned wells aims at early detection of any leakage taking place through an abandoned well.

A generic monitoring strategy for abandoned wells in CO_2 storage sites has been developed as part of this report. The monitoring strategy commences with gathering all relevant data about each well that might present a potential leak path for CO_2. Considering well and field configurations, risky wells are defined and included in the monitoring network. Specific monitoring methods are selected for each of the wells. Both, the monitoring methods and the network will be highly site-specific and it is very likely that selected monitoring methods will vary between wells in a specific location. Measurements will be repeated frequently during injection period. The monitoring strategy will be regularly updated based on new information. To ensure integrity, monitoring efforts are required to continue until the stabilization of the injection zone is confirmed in the post-injection phase of the project before the site is transferred to the competent authority. Remedial actions would be required if the containment of the site would be compromised.

In most cases, monitoring options for abandoned wells will be limited to indirect geophysical methods conducted from the surface (or from monitoring wells) in combination with sensors installed and sampling at the near-surface/groundwater/air.

One of the most common and sensitive methods that can be used to monitor abandoned wells is repeated seismic reflection surveys. Other methods include self-potential and repeated electromagnetic surveys. However, these methods currently offer limited resolution compared to seismic reflection. Cross-well or well-to-surface measurements can be used to increase the resolution of these methods, but these will increase the monitoring costs significantly due to the drilling of extra wells.

Direct monitoring methods can only be applied to abandoned wells, if the well is re-opened. Most of these methods will only help to find the location/extent of a leak and evaluate the integrity of the rest of the wellbore. Downhole pressure and temperature sensors (discrete or DTS) can also be installed in the wellbore (above primary or secondary cement plug) while the well is open, and provide continuous data flow even when the well is re-abandoned. The main problem with current sensors in the industry is that because of their limited life expectancy (generally 5-10 years), they will need to be replaced (more than once) during the duration of the project. Technological developments such as the possibility to replace optical fibres offline are essential to tackle this problem. Moreover, any data cable/fibre running from surface into the well will introduce a new leak path within the hole. The efficiency of available downhole sensors in abandoned wells in terms of instrumented abandonment could be tested in re-opened abandoned or accessible wells, e.g. in short-duration projects such as pilot sites.

Due to the increasing number of ongoing research projects associated with CO_2 storage, it would be beneficial to conduct a survey on new available monitoring technologies prior to each new project to optimally prevent and detect wellbore leakage.

Initial measurements should be taken prior to the start of injection to establish baseline values. The monitoring efforts will continue throughout the injection with regularly repeated surveys and correlation with other relevant aspects of the storage operation, including the entire monitoring network. The performance of the monitoring operations should be regularly evaluated and, if needed, adapted according to the updated requirements. After injection has been stopped, monitoring needs to continue until it is confirmed that the formation has been stabilized and no leakage has occurred.

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Appendices

Appendix A Streaming Potential method to detect leaking CO_2 from (abandoned) wells or any other leakage situation

A.1 Introduction

A.1.1 Framework

The Work Package 3-4 of the CATO program covers many issues about Well Integrity. Of this WP, Task 3.4.3 is “Monitoring well integrity” of which one of the tasks is “Developing strategies to monitor abandoned wells”. The problem of abandoned wells is that no access can be gained to the wells. The wells are generally old. The current status of its integrity can therefore not be assessed by more standard measurements (in the well). The location of the well is generally known.

One of the options to assess any possible problem related to such an abandoned well is to monitor the leakage coming from that abandoned well. One way to detect such a leakage may be to detect the streaming potentials that such leakage causes. Streaming potentials originate when an electrolyte is driven by pressure gradient through e.g. porous media with charged walls. Streaming potentials are known in the geophysical field, but not generally and widely applied. The subject of this appendix is to evaluate the usage of streaming potentials for CO_2 leakage of abandoned wells. This is not only relevant for abandoned wells, but for any installation where leakage is to be detected. In fact it may be relevant as well for subsurface production and injection systems. The main question is whether the amplitude of the signal is large enough to be detectable. Some way of stacking the measurements, which is easily realized employing a permanent electrode array, may increase the signal to noise ratio significantly.

A.1.2 Streaming potential

Several studies have been carried out recently on SP modeling, laboratory work and field work.
A nice overview is presented in Sheffer (2007), although with emphasis on shallow applications.
Wurmstich and Morgan (1994) did work on modeling streaming potentials caused by oil well pumping. Saunders, J. H., M. D. Jackson, and C. C. Pain (2006) developed this work further. Moore et al. (2004) describes laboratory experiments on samples of sandstone for assessing the coupling coefficient determined before and after liquid CO2 passed through the specimens displacing all mobile pore water.

Measurement of SP in the field is for several practical situations hampered by the low amplitude of the signal (the signal decays fast with distance from the source). The reason for considering SP is that although the signal may be small, it might become detectable with modern multi-channel data acquisitions systems and state of the art processing techniques.

A.1.3 Activities carried out

A combination of modeling and measurements in the laboratory was carried out.

Modeling can help to understand the streaming potential process. Analytical modeling for homogeneous models gives insight in the decay of the potential with distance (depth) and the general shape of the anomaly. Numerical modeling can verify this (or itself) and can be used to incorporate inhomogeneities in the subsurface. However within the framework of this work package it was not possible to setup a numerical model.

The measurements were done in the laboratory in a tank. It was only possible to carry out some initial measurements; much was learned about noise and electrode behavior. It was also necessary to develop some processing algorithms to make the SP-effect visible.

A.2 Streaming Potentials Modeling

A.2.1 General

Streaming potentials are a result of fluids flowing in a porous medium. An electrical boundary layer is present at the solid-fluid interface when the solid surface becomes electrically charged (because of chemical interaction with the fluid). The boundary layer consists of an adsorbed layer of tightly and more loosely bound ions of countercharge. Under static conditions, the saturated medium is electrically neutral. As the fluid starts to flow, excess charge from the boundary layer travels in the direction of the flow, resulting in an electrical current. The charge imbalance induced by this movement generates an opposing conduction current. The streaming current is limited to the pores, the conduction current permeates the entire medium and maybe detected by self potential measurements.

The streaming potential is described by the following equation:

$$j = -L_x grad(p) - \sigma grad U_s$$

where j is the electrical current density (A·m^{-2}), L_x the current cross-coupling coefficient (A·m^{-2}), grad(p) the gradient of a hydraulic potential gradient (dimensionless), σ the conductivity and grad U_s the gradient of an electrical potential.

Thus the current density is the sum of the current density related to the water flow and that of the "standard" Ohmic conduction.

Some authors (e.g. Wurmstich and Morgan, 1994) state that only poor knowledge exists about the cross-coupling properties. The electrokinetic coupling term L_x depends on (Saunders et al., 2006) the zeta potential, the dielectric constant of the pore water, the electrical formation factor and the water viscosity. Sheffer (2007) however indicates that laboratory studies and literature data suggest that the cross-coupling factors do not vary over a wide range.

In practice often the streaming potential coupling coefficient C is used, also as it can be measured in the laboratory. It is given by:

$C = -L/\sigma$, and thus $C = \Delta U/\Delta h$,

where U is the electrical potential and h the hydraulic head.

Since the model parameters: permeabilities, cross-coupling properties, and electric conductivities depend on a few basic rock-physics parameters such as brine conductivity, amount of water saturation, and porosity, the model parameters should be evaluated self-consistently using rock-physics models.

Wurmstich and Morgan (1994) in their article related to streaming potential measurements for oil well pumping, state: “The streaming potential response depends on brine conductivity, conductivity structure, well casing, and reservoir dimensions and decreases rapidly with distance from the production well. The parameterization of the models establishes bounds for the expected streaming potential response that varies by approximately one order of magnitude. Because of the ac nature of pumping processes, signal stacking could perhaps be used to make the expected small signals discernible. Our models are mainly limited by poor knowledge of in-situ, cross-coupling properties.”

A.2.2 Homogeneous subsurface

Sheffer (2007) gives an analytical solution of the electrical and hydraulic potential at the surface for a point source in a homogeneous medium (half-space). It is given by the following two expressions:

$$h = -Q/2\pi K|r - r_s|$$

$$V = hL/\sigma$$

with:
h = hydraulic head (m)
Q = volumetric flow rate (m^3/s)
K = hydraulic conductivity (m/s)
r = evaluation location
r = location of the source
V = electrical potential (V)
L = cross-coupling coefficient (A/m^2)
σ = electrical conductivity (S/m).

As an example the response of a leakage displacing 2400 m^3 water/day at 125 m depth is shown in Figure A.1. For this case, the hydraulic conductivity is 10^{-4} m/s., L = 10^{-5} A/m^2, and σ = 1 mS/m. These values correspond to a sandy subsurface, filled with fresh water.

Each parameter that influences the response will be discussed in a separate section.

A.2.2.1 Volumetric Flow Rate

This parameter corresponds to the volumetric rate of the water displaced by the CO_2 leakage and is thus related to the amount of CO_2 that leaks at a certain point. The value of the parameter should be derived from what is seen as a dangerous situation with respect to CO_2 leakage.
The leaked CO_2 (mass) must be converted to a volumetric amount. How this can be done is exemplified in Figure A.2 (prepared using webbook.nits.gov).

As an example we consider leakage of 5 tons per day (an amount that leaks from the Latera or Ciampino location in Italy). The corresponding volume at depth can be derived from the figure. At depths ranging from 300 to 600 m, pressure ranges from about 30 to 60 bars and the corresponding volume from 77 to 25 m^3 per day.

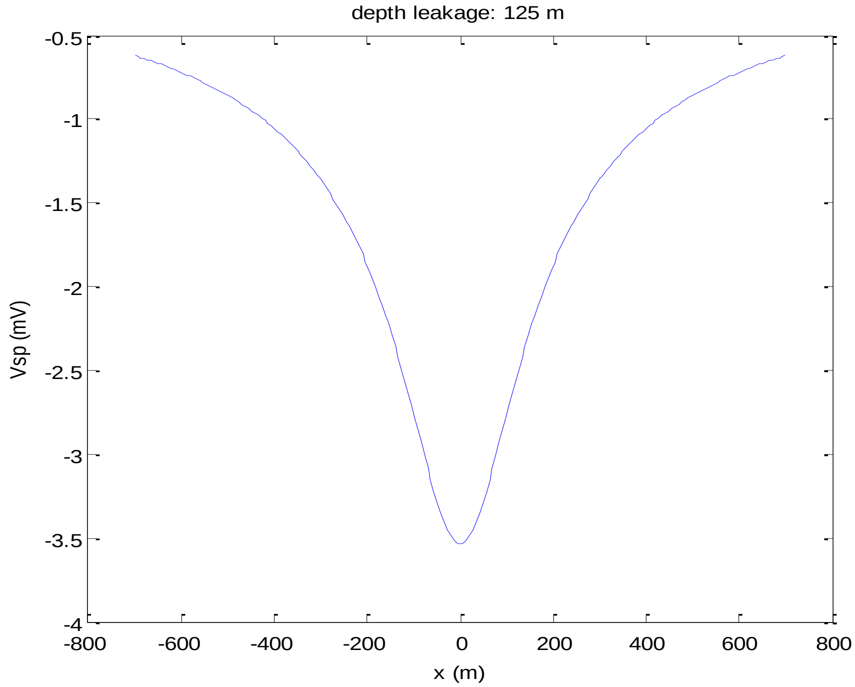

Figure A.1 Electrical response at the surface for a leakage at 125 m depth in a homogeneous medium.

Another approach to find an estimate of a relevant Q is to consider injection rates at CO_2 storage sites. For Sleipner about 1 million tons of CO_2 per year is stored at a depth of 1120 m, for K12-B: 20 ktons/year. These two amounts differ a factor of 50. For now, we assume that a leakage larger than 1% should be detected. For Sleipner this would amount to 10 ktons/year, corresponding to 27 ton per day. If this amount leaks from depths in the range of 600 m - 250 m, the volume corresponds to 135 - 540 m^3 per day.

Still another source to find relevant leakage volumes is Wright (2012), who writes about leakage types and considers:
a high discharge (e.g., >200 tonnes per day) point source leakage (due to acute well-casing leakage or hydro-fracturing of a seal cap) in a relatively small depleted reservoir site, and
a low discharge (e.g., <20 tonnes per day), dispersed source discharges from an extensive saline system.

Consider 200 tonnes per day, as the lower boundary of a high discharge, from a well at 300 m depth, this corresponds to a volumetric displacement of 3200 m^3 per day.

Here we summarise that relevant leakages to detect vary from about 1 to several hundred tons of CO_2 per day. Depending on the depth this corresponds to a volumetric flow rate as can be determined from e.g. Figure A.2.

It should be noted that it is also obvious from Figure A.2 that the shallower the leakage the larger the volume of displaced water for a fixed mass of CO_2 leakage.

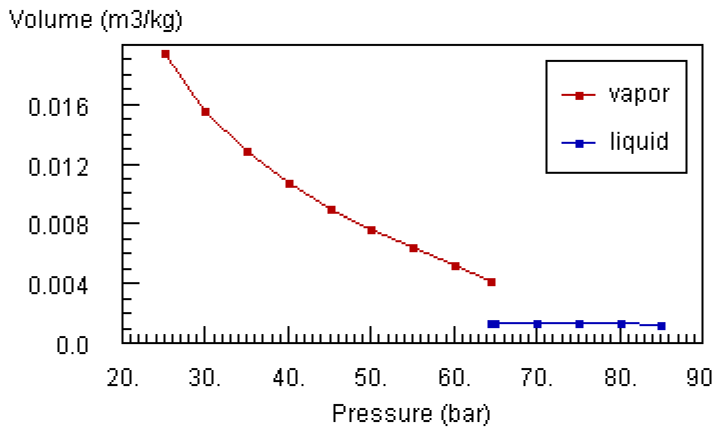

Figure A.2. Volume per weight of CO_2 (25°C) versus pressure (from webbook.nits.gov).

A.2.2.2 Hydraulic conductivity

The hydraulic conductivity is a parameter of the subsurface describing how easy water flows through the pores. Gravel and sands have high hydraulic permeability, whereas clays and peat have typically low hydraulic conductivities.

Values range from more than 0.002 m/s for gravel, to 5E-05 m/s for fine sand to less than 1E-10 m/s for clays.

As the range is so high (8 decimals) , the hydraulic conductivity can influence the SP-response to a large degree. The measured potential increases with decreasing hydraulic conductivity (for a homogeneous half-space).

A.2.2.3 Cross-coupling effect

It is noted by some that the models are mainly limited by poor knowledge of in-situ, cross-coupling properties. Sheffer (2007) however indicates that laboratory studies and literature data suggests that the cross-coupling factors do not vary over a wide range.

Measurements in the laboratory have been performed to estimate the streaming potential cross-coupling coefficient. It can also be estimated using complex formulae that involve many parameters.

Sheffer (2007) carried out different types of laboratory measurements to determine L. It is concluded that L varies within one order of magnitude for typical geological materials. Thus its value influences the estimate of the potential at the surface not so much as e.g. hydraulic conductivity and electrical conductivity.

A value of 2E-05 A/m^2 can be considered a useful value for the calculations here.

Moore et al. (2004) determined the coupling coefficient determined before and after liquid CO_2 passed through laboratory specimens of a certain sandstone. The CO_2 displaced all mobile pore water. Results on five samples averaged approximately to -30 mV/0.1 MPa. After liquid CO_2 passed through the specimens displacing all mobile pore water, trapped water remained and the coupling coefficient was approximately -3 mV/0.1 MPa. Our comment is that the permeability is needed to compare these numbers with those given by Sheffer.

A.2.2.4 Electrical conductivity

The electrical conductivity, or its reciprocal, the electrical resistivity can vary over several decades for different soil/rock types. The conductivity for sands and gravels is attributed to the water in the pores. Saturated clays have a higher electrical conductivity (e.g. 0.08 S/m) than saturated sands (e.g. 0.01 S/m). For sediments, the electrical conductivity depends to a large degree on the electrical conductivity of the water contained in the sediment. Archie's law is generally used to calculate the electrical conductivity of the rocks from the electrical conductivity of the water and some other parameters.

The measured potential increases with decreasing electrical conductivity (for a homogeneous half-space).

A.2.3 Modelling the laboratory experiments

The estimated values for the laboratory experiment are initially as follows:

- volumetric flow rate: 56 ml was injected in about 10 s, so that Q = 5.6 .10^{-6} m^3/s.
- the hydraulic conductivity of (somewhat coarse) sands is taken to be 0.0001 m/s.
- the electrical conductivity of the (water saturated) sand is estimated to be 0.01 S/m.

The resulting results of themodelling are shown in Figure A.3. It shows a variation of the SP from a few hundreds to about 1500 µV. The anomaly modelled is about ten times larger than the anomaly observed. The parameters used in the modelling should probably be modified somewhat to find a better fit with the modelling.

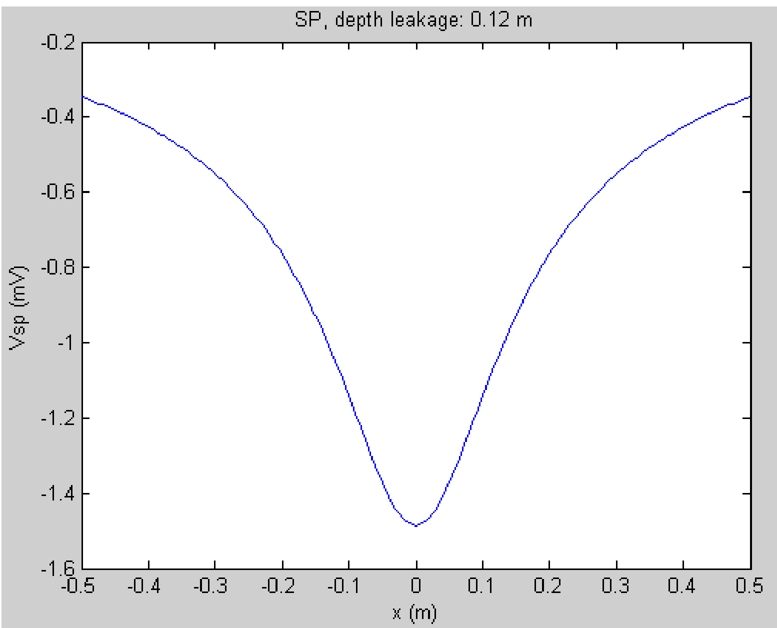

Figure A.3 Model results of the laboratory experiments.

Now, considering that $V = -Q.L/(2\pi\sigma K|r - r_s|)$, it is seen that increasing K and/or sigma lead to lower electrical potentials. These are parameters that show large ranges in practice. For laboratory experiments, K = 0.0005 m/s and σ= 0.02 S/m would also be acceptable parameters and do explain the amplitude of the anomaly.

The shape of the anomaly in the tank is not so well defined and not so repeatable (see Section A4 on experiments).

A.2.4 Parameter ranges for possible use of SP

We can define an amplitude of anomaly ($Vthr$) above which we consider the SP-method as useful. We can then derive ranges for volumetric flow rate, hydraulic conductivity (m/s), depth and sigma that would correspond to such an anomaly in a homogeneous subsurface (L is considered rather constant).

Considering the amplitude just above (or near) the abandoned well, $|r - r_s|$ becomes the depth. We then have that:

$$Q/\sigma.K.depth > 2\pi.V_{thr}/L$$

For a specific "geological" environment σ and K are defined and the relation between the volumetric flow of the water and the depth of the leakage that is detectable can be determined from:

$$Q/depth > 2\pi.\sigma.K.V_{thr}/L$$

We now take several cases for which the right part is "known" and called here "local geological conditions parameter" (LGCP) a relation between the leakage depth and the size of the leakage is found:

$$Q > depth.LGCP$$

	Sand environment	Sand/Silt environment	Silt environment
K (m/s)	5 * E-04	5 * E-06	5 * E-07
Sigma (S/m)	0.01	0.025	0.05
L (A/m^2)	2 * E-05	2 * E-05	2 * E-05
V_{thr} (V)	1 * E-03	1 * E-03	1 * E-03

The minimal leakage versus depth for a homogeneous subsurface is depicted in Figure A.4. It is seen that for highly permeable rocks, that may be the more relevant with respect to risk, the SP technique is less sensitive. For less permeable environments the method becomes more sensitive.

A.2.5 Inhomogeneous subsurface

In real situations we always have to deal with an inhomogeneous subsurface.

To model streaming potentials in an inhomogeneous subsurface a finite volume discretization code must be used. Within the framework of this work package it was not possible to make such a complex code operational. Here we confine ourselves to some general remarks.

It can be shown that in an inhomogeneous subsurface the electrical sources can be split in a primary source, related to the groundwater flow (leakage) and secondary sources generated by transitions (gradients) in hydraulic conductivity, cross-coupling coefficient and hydraulic head. Furthermore, gradients in sigma will influence the streaming current distribution and can be considered as secondary sources. Whether the inhomogeneities augment or diminish the amplitude of the anomaly cannot be said in general, it depends on the specific electrical conductivity distribution.

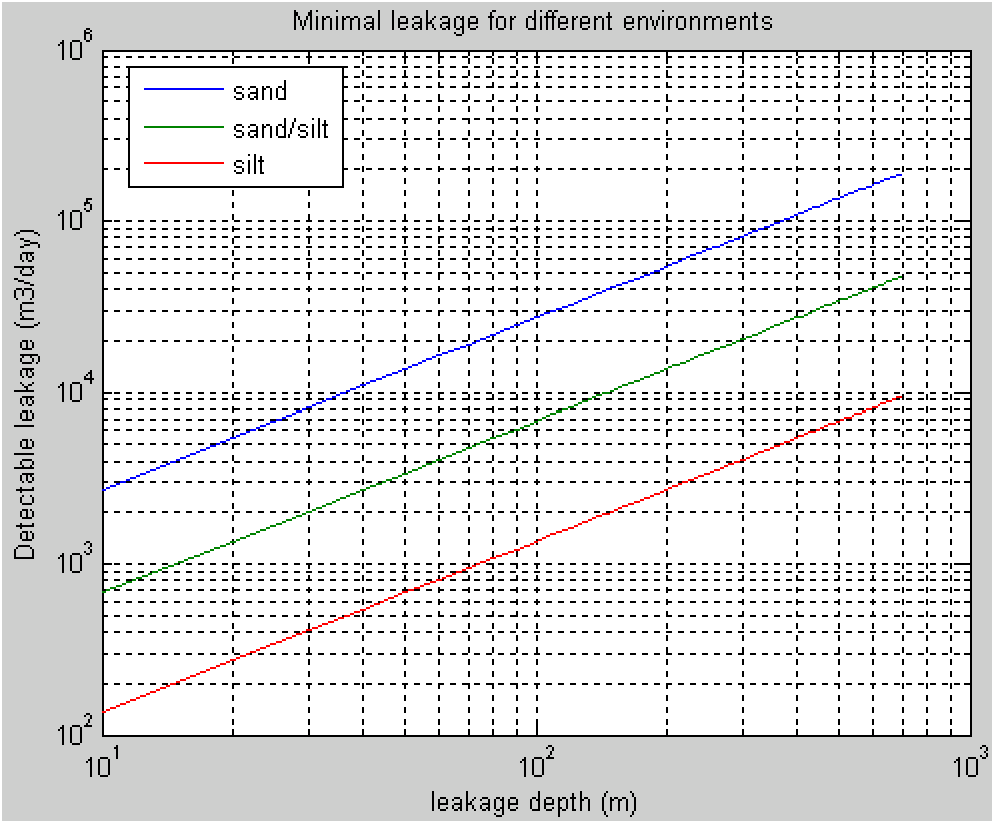

Figure A.4 Detectable leakage (water displacement) versus depth for three geological environments for a homogeneous subsurface.

A.3 Measurements

A.3.1 Box and Fill

First experiments were done in a small plastic box: 21 cm x 24 cm with a sand height of 11 cm. The volume of the sand is then about 5544 cm^3. The sand is "Karwei" silver sand. For a porosity of 35% the pore volume amounts to 1940 cm^3. A syringe of 60 ml (= 60 cm^3), in practice filled to 56 ml, was used to inject water in the dry sand.

A second series of measurements were carried out in a box (box 2) in which first 25 kg 'zilverzand' and then 25 kg 'ophoogzand' was dropped. The surface of box 2 is 55 cm * 36 cm (= 1980 cm^2). It was filled with a column of 18 cm of sand. The volume of the sand is then: 35640 cm^3. For a porosity of 25%, this volume of sand can hold 8,9 l of water, for 35% of porosity 12,4 l. From the analysis of the amounts of water added and the moment the water level reached the surface it is concluded that the porosity is in the order of 33 %.

For each injection experiment about 56 ml of water is injected. This corresponds to about 0,45 % of the total pore space. After each experiment the volume of water increases, although in between measurements water will also evaporate; e.g. between July 21st and August 15th the sand completely dried.

The water was injected at slightly different speeds leading to different amplitudes of flow.

The importance of the capillary forces was not realized when carrying out the experiments. It is seen from Figure A.5 that the capillary height increases within minutes for sand, which means that the electrodes were almost always placed in the capillary fringe, except maybe for the very first experiments, and not, as thought first, in the dry zone above the water table. That the electrodes are within the capillary zone means that the electrodes are in electrical contact with the "groundwater" and that no high resistive zone is present around the electrodes. This contact with the groundwater which makes the measurements generally of higher quality.

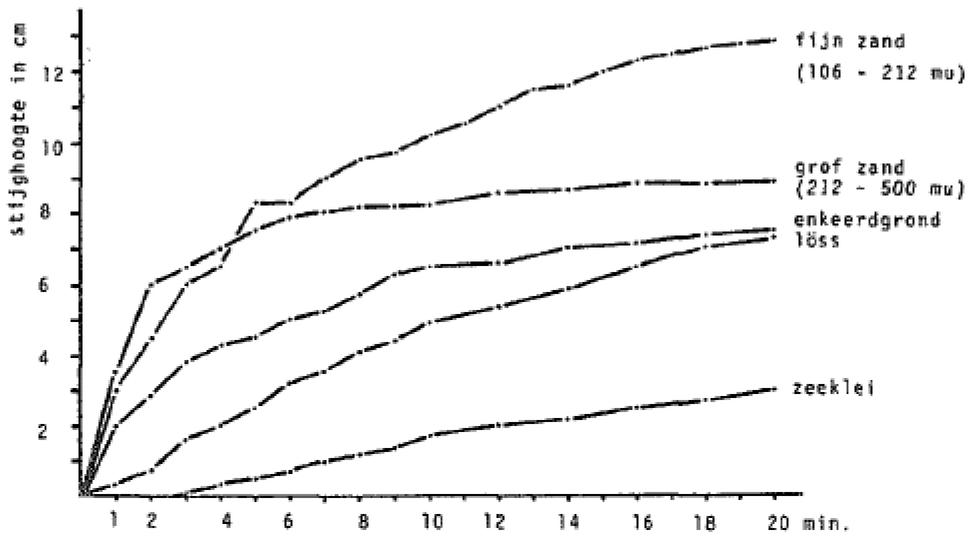

Figure A.5 Capillary height versus time for various soil types (Rutgers, 1983)

A.3.2 Data acquisition

Voltage recording was done with an Agilent U-2351A device connected to a pc (usb). It has an entrance impedance of 1 GOhm and allows 16 channels to be recorded (single ended) at various sample rates. It has a 16 bit resolution and the most sensitive input range is ±1.25 V. Therefore the last bit represents 38 or 19 µV (depending on how the bit sign is treated).

A board of 16 passive first order low pass filters (10 µF and R = 15 kOhm) was built to reduce any interference of high frequency signals and fulfill the Nyquist criterion.

The internal noise of the instrument according to the specifications is 1mV rms. This is relatively high, but this high value was only later discovered, after having contact with Agilent about measurement results, and the noise observed.

A.3.3 Electrodes

The importance of selecting the right electrode might be easily overlooked. In the experiments two types of electrodes were used: stainless steel and non-polarizable electrodes (NPE's).

A.3.3.1 Stainless steel nails

The nails used were bought in a standard "Karwei" type shop of a few centimeters length, stainless steel according to the label.

A.3.3.2 NPE

The NPE's were bought from the French company SDEC (http://www.sdec-france.com/) called the PMS9000. The technical specifications of the NPE's are as follows:
- Diameter : 32 mm.
- Length : 180 mm.
- Weight : 250 g.
- Value of the polarization on new electrodes : about 0,2 mV.
- Drift : ≈ 0.2 mV per month.
- Temperature factor : 20 à 30 µV/°C.
- Internal resistance (value between 2 electrodes) : ≈ 500 Ohm.

They were placed such that the tip of the electrodes was approximately 8 cm below the top of the sand.

A.3.4 Types of measurements

The following types of measurements were carried out:
- passive
- active: applying current through two current electrodes
- passive during water injection: the SP measurements

The passive and the active measurements were done to understand the measurements and see a bit of electrode and system response. During the active measurements a current is applied to two electrodes (stainless steel nails). In the first active recordings the current was only measured with a standard multi-meter. Later on the current was measured versus time, using a voltage measurement over a resistor of low resistance.

A.4 Measurement Processing and Analysis

A.4.1 Introduction

Data are analyzed by:
- visual checks on standard measured voltage-time graphs
- various spectral analysis plots
- trend analysis routines as explained in the next section
- map views of values/anomalies.

Data are analyzed mainly using MATLAB scientific computing environment.

A.4.1.1 Band-pass filtering

A band-pass filter, with a relative low high-stop frequency (e.g. 2 Hz) was often applied to suppress 50 Hz and other noise interference.

A.4.1.2 Moving average

A moving average of varying window length was sometimes used to average the relative high frequency noise and get a better view of trends in the data.

A.4.1.3 Trend analysis routine (trendan)

A special MATLAB script (trendan) was developed to determine any (relative) sudden change in the data, possibly related to water flow. The trendan routine carries out a trend analysis over subsequent time windows: the measured V is fitted to V0 + A*t over a time window of user defined length. The window step defines the interval between adjacent start times for the time windows. The value of A is plotted versus time. A is expected to change for time windows in which water is added. As an example of how trendan behaves an SP-signal of short duration was superposed on white noise was simulated. Two signals consisting of white noise were created (min/max amplitude: -0,5/0,5). A local “blub” of amplitude 0.1 was added to signal 1 (Figure A.6).

The trendan curve for the slope shows a two-lobe changing sign anomaly, whereas the V0 (C0 in the plot) coefficient will show the anomaly itself with some side lobe effects.

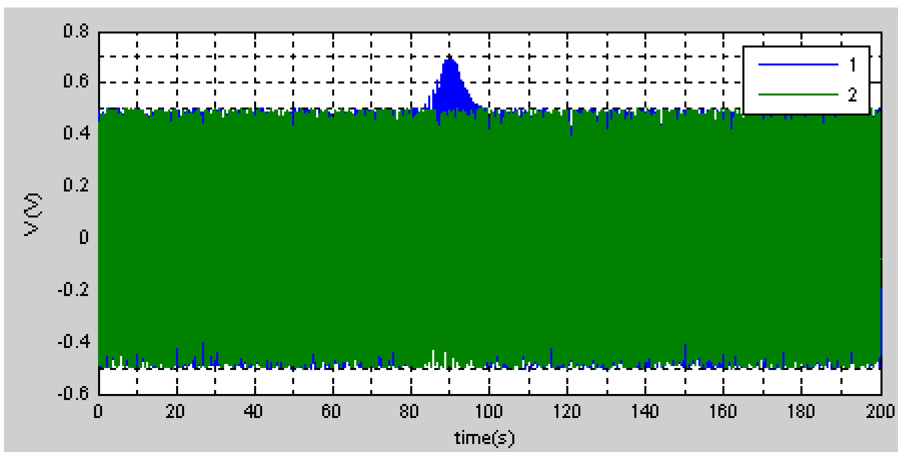

Figure A.6 Voltage anomaly with random noise on channel 1.

A.4.1.4 Detect amplitude level change

It is observed that the signal amplitude changes over a longer period than the duration of the injection. Therefore another way to enhance the detection on an injection is to compare the mean signal level at some time window with that over an adjacent time window.

Figure A.8 shows the output of such an algorithm for the data in Figure A.6. In fact the data here does not have a step-wise behaviour, but more a bell-shaped amplitude behaviour.

An example of measured data and the two event detection routines applied is given in Figure A.9.

It is seen that the two event detection methods perform in a comparable way.

Figure A.7 Result of trendan on data in Figure A.6 for different window lengths`(V0 left, Linear slope right).

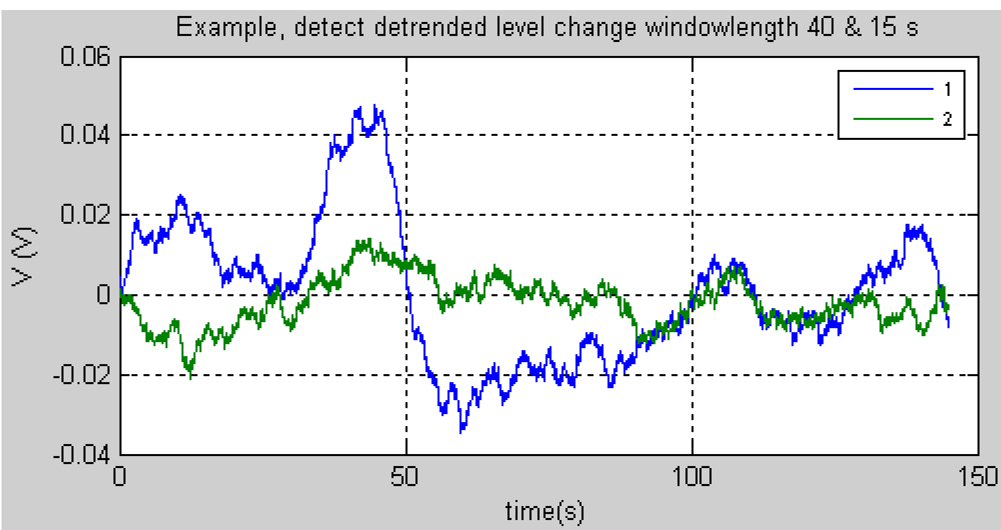

Figure A.8 Example of detect level change output for the data in Figure A.6

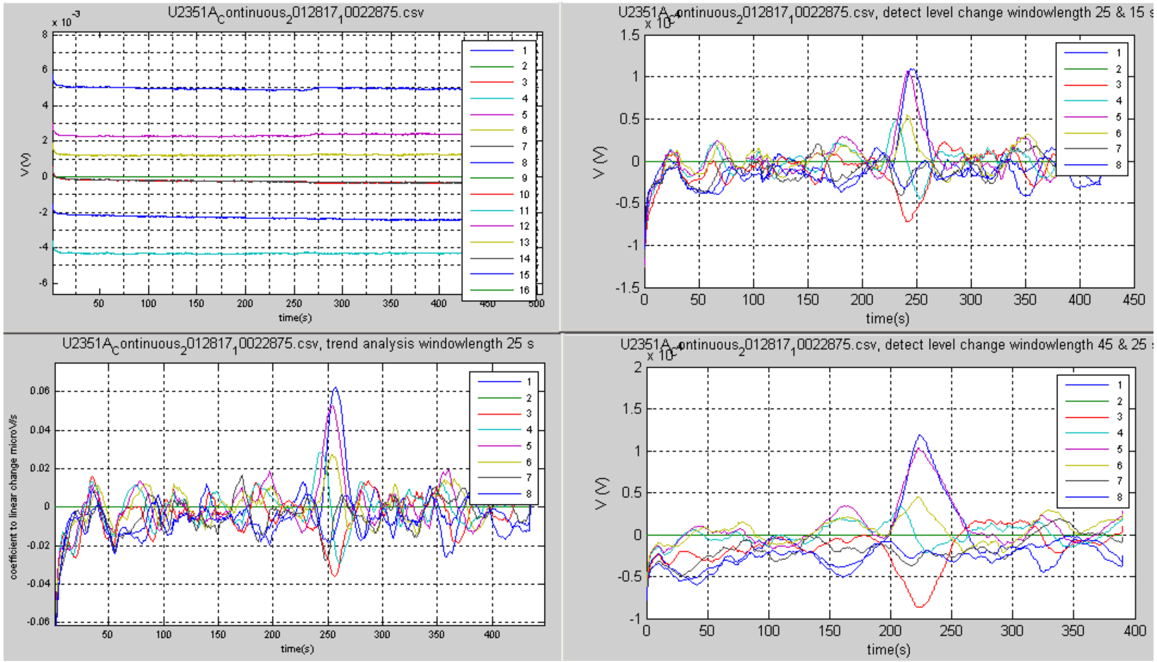

Figure A.9 Data (upper left) from box experiment, trendan analysis (lower left) and detect level change (right) for two different window settings.

A.4.2 Data analysis measurements in Box 2 - passive measurements

A typical example of a noise record is shown in Figure A.10. Channels 1 to 12 are connected to the PMS9000 electrodes, channels 13 to 16 to the stainless steel nails.

It is seen that the stainless steel electrodes show a high bias and a time varying component in the signal with a response time of a few hundred seconds. The PMS9000 electrodes do not show this behaviour.

The data do suffer from band limited noise as can be inferred from Figure A.11, where no moving average was applied. Obviously there is still noise from the 50 Hz net, but also noise around 47 Hz and 60 Hz. As yet it is not clear where this noise comes from. It is probably related to the data acquisition unit (Agilent) in combination with the low amplitude of the variation of the potential. Changing the sample rate, does change the noisy bands as can be seen from Figure A.12.

Apart from the power noise of 50 Hz (and 150 Hz), the noise bands are now around 54, 59, 67 and 78 Hz. Agilent was contacted to comment on this noise. After much e-mail contact it was concluded that the internal noise of the recorder used is 1 mV rms. A more expensive recorder with lower internal noise specification would probably not show this behaviour. The “cause” of the noise was not clarified.

The “background” value of the PMS9000 measured signal is probably characteristic for the specific electrode or the local conditions (humidity, temperature) around the electrode as there seems to be no aerial pattern in this background value.

A passive measurement was conducted (May 13th) The amplitude of the anomaly over the twelve NP-electrodes is depicted in Figure A.13.

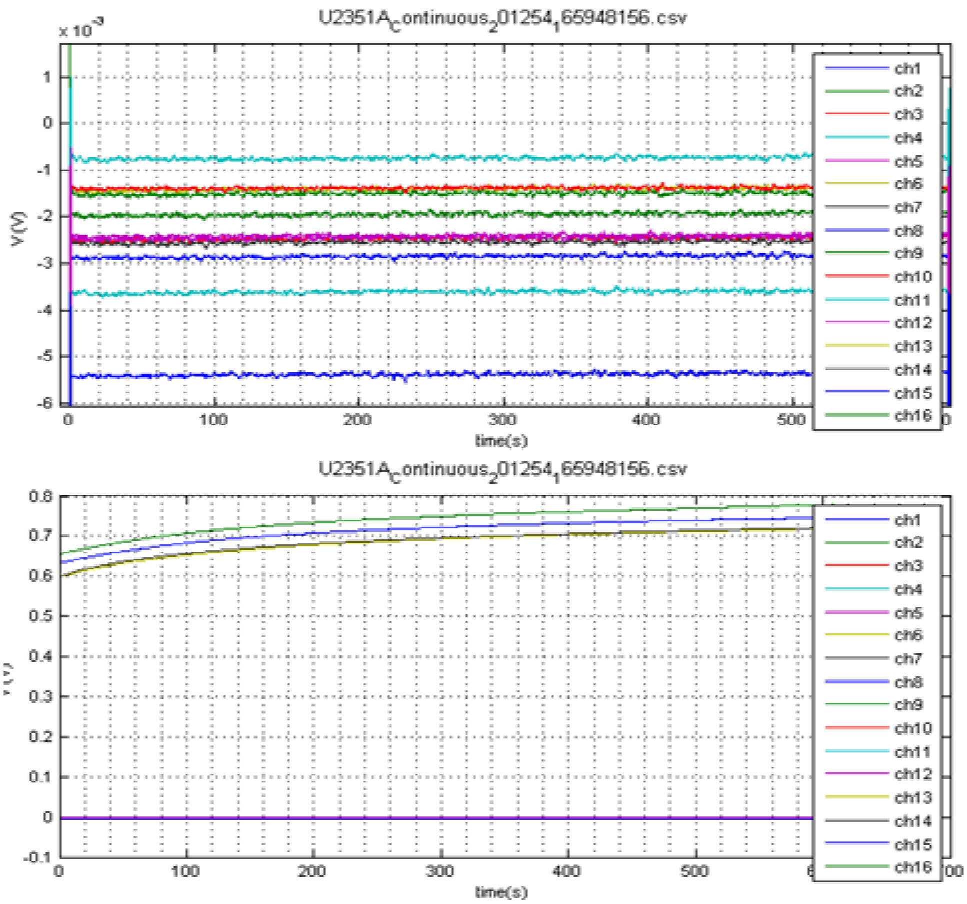

Figure A.10 Data record without activity; on top a detail for the NPOL electrodes (ch1-ch9), below all electrodes. Data are averaged over a 2 s window.

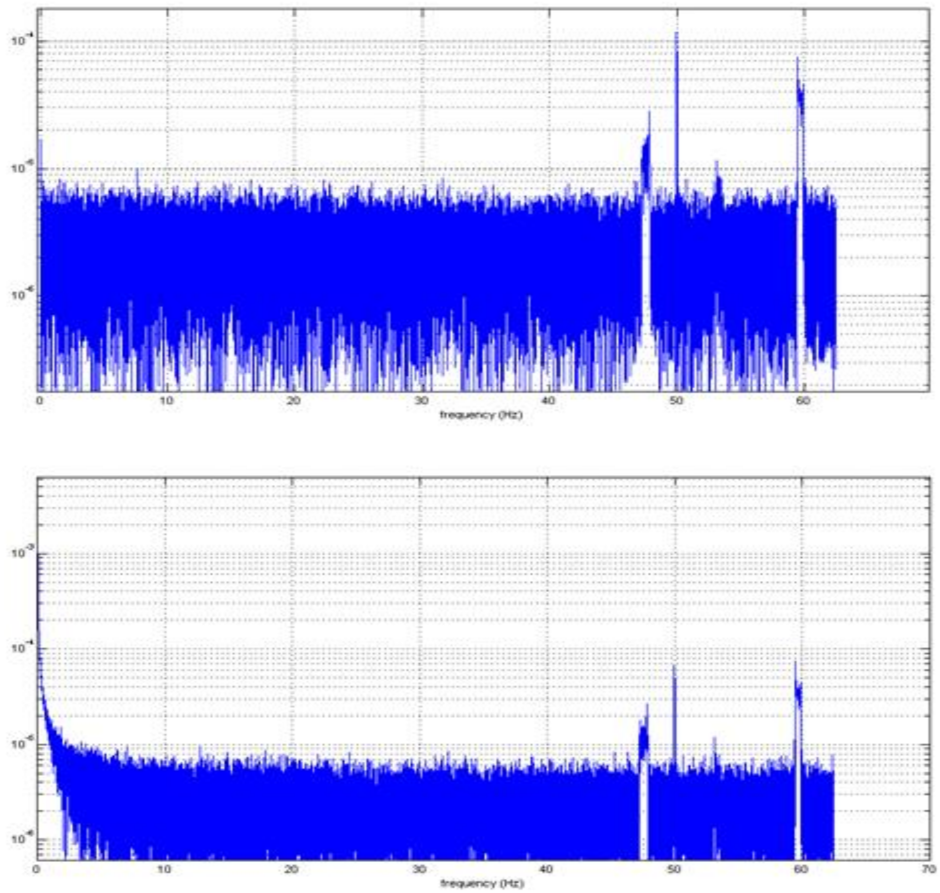

Figure A.11 Spectra from passive recording of ch7 PMS9000 (upper) and ch14 stainless steel (lower) electrode.

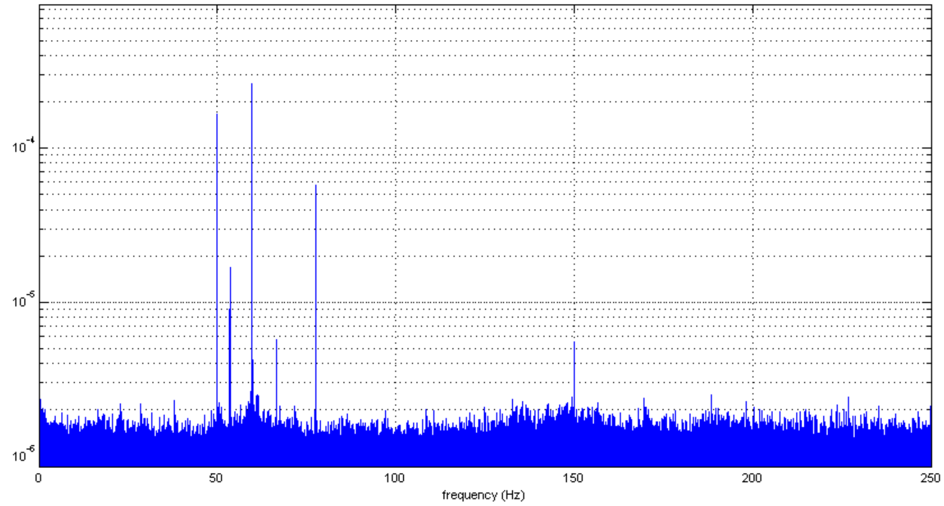

Figure A.12 Spectrum of ch7 for no activity with a sample rate of 500 samples/s (no moving average).

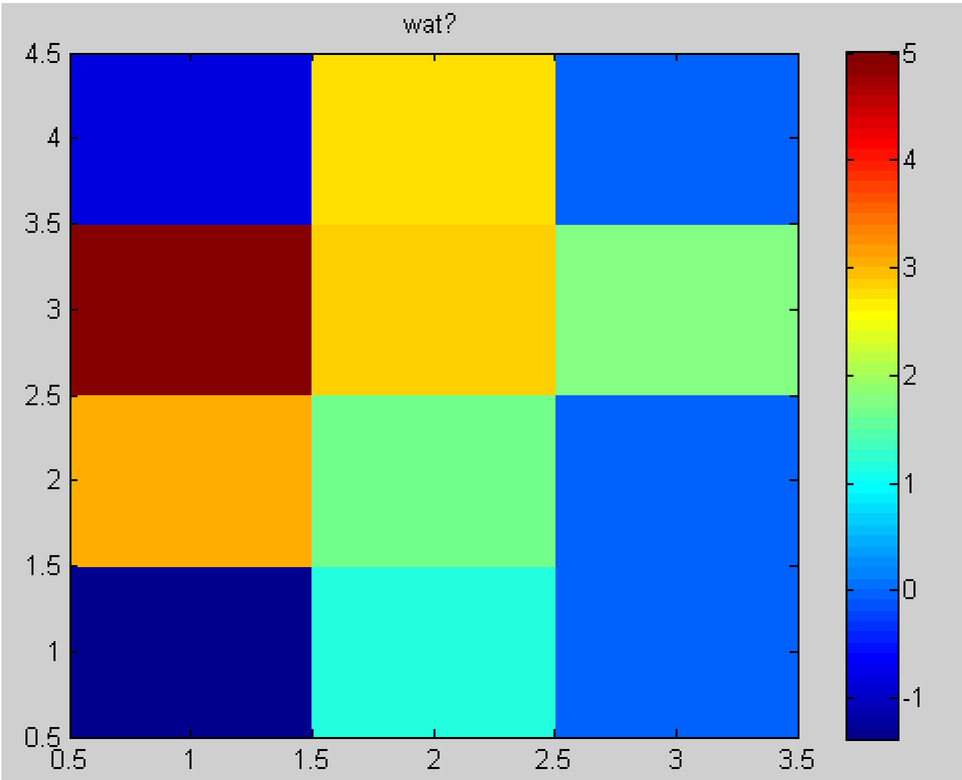

Figure A.13 Amplitude of the SP-value mapped over the twelve electrodes (experiment May 13-2).

The image probably reflects somewhat the humidity of the (basically dry) sand.

A.4.3 Data analysis measurements in Box 2 - Active measurements

Firstly 3 liters of water was added to the box. Then an active measurement was carried out, i.e. a current was driven through 2 current electrodes (nails) pushed in the surface of the sand. Examples are given in Figure A.14 (current injection from 8 – 20 s and 55 – 66 s) and Figure A.15 (current injection from 10 – 61 s and 80 – 163 s).

Noteworthy was that the measurement shows that a different equilibrium state was achieved for the two types of electrodes. The PMS9000 instantly react (only visible is the response of the analogue low pass filter), whereas the stainless steel electrodes have a longer response time of about 3 s. It must be concluded that some electrochemical reaction at the stainless steel electrodes requires some time to stabilize.

It is seen that the potentials slowly decrease in amplitude with the current on. This is probably related to interaction of the current electrodes with the sand/moisture. This is also reflected in the fact that the absolute value of the current slowly diminishes during both first and second transition periods.

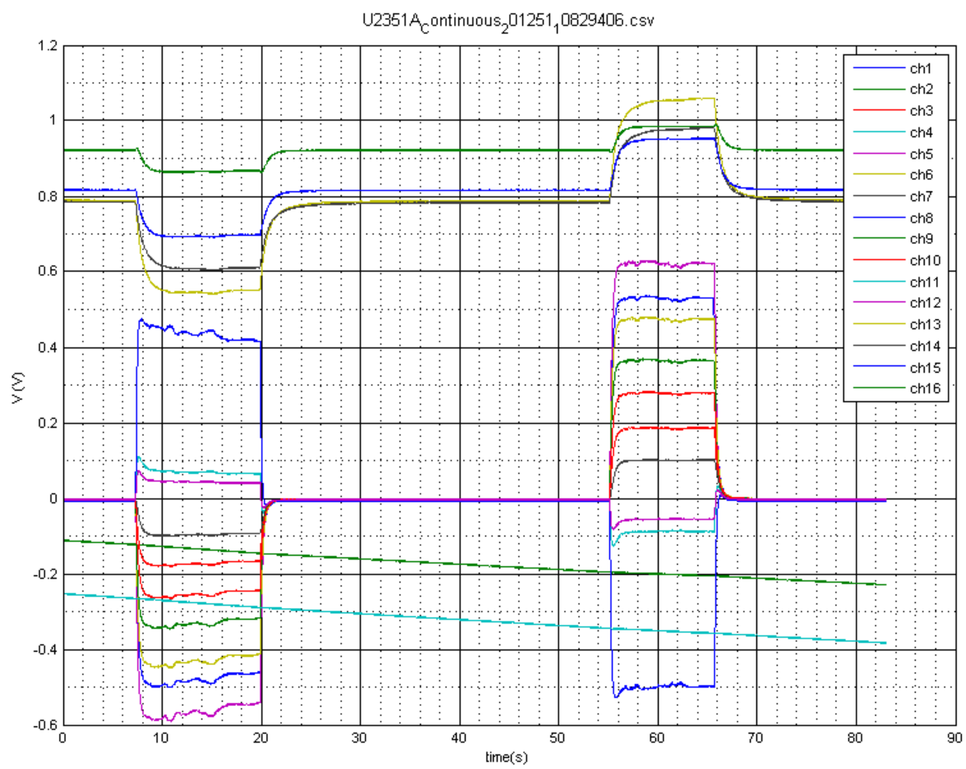

Figure A.14 Measurement with active source.

The varying behavior in the second source-on period corresponds to the variation of the current observed (only in log book, not recorded).

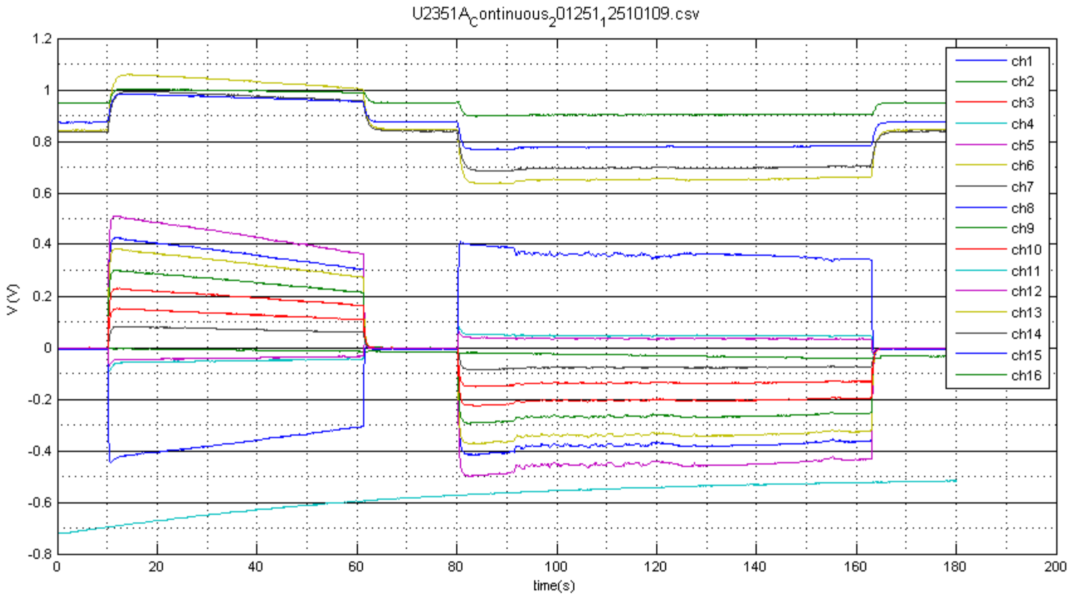

Figure A.15 Measurement with active source (20 Sa/s).

A.4.4 Data analysis measurements in Box 2 - Water injection monitoring

The detection of any response to water injection is determined using a MATLAB script (trendan) that was developed for this purpose. This routine employs a window length. It is implemented in such a way that any response is already seen one window length before the injection activity.

An example of data and the C0 and C1 is shown Figure A.16, Figure A.17 and Figure A.18. Water (60 ml) was injected from 130 -150 s and from 350 - 368 s: 60 ml. The anomaly around 520 s is some artefact (movement of electrodes?). Although the streaming potential can be observed in the raw data for some channels, most notably the nearby channel 3, for others the response is not so visible in the raw data. The C0 and especially the C1 coefficients enhance the streaming potential response to the water injection.

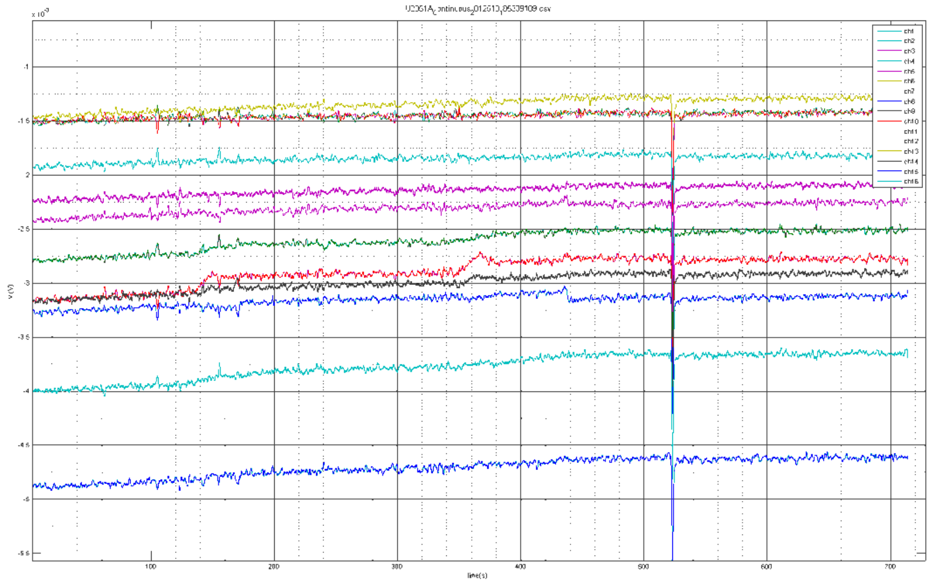

Figure A.16 Raw data (window averaging of 1 s) PMS9000 electrodes during water injection.

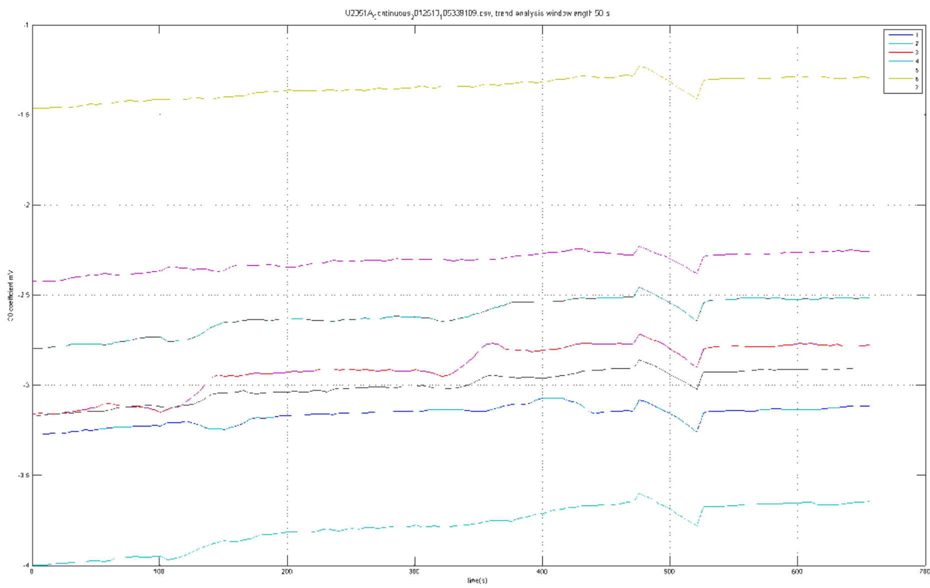

Figure A.17 C0 coefficient of first 7 channels during water injection.

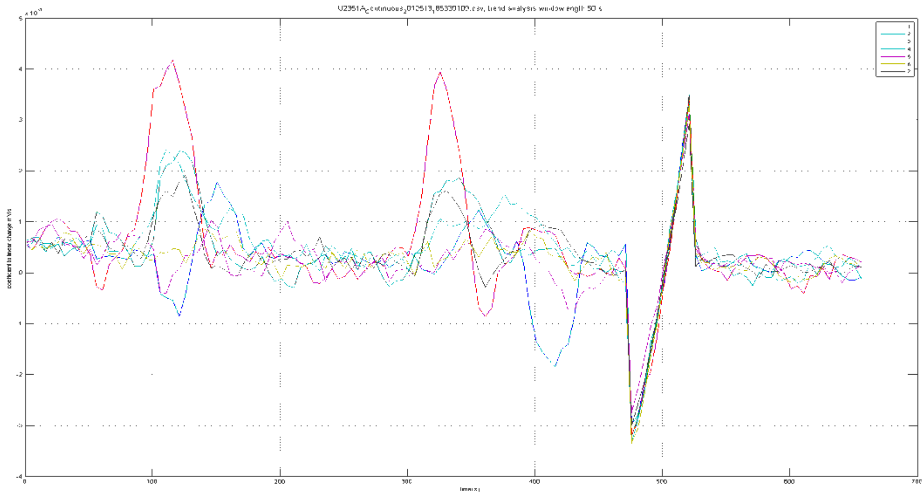

Figure A.18 C1 coefficient of first 7 channels during water injection.

A.4.4.1 Second example

Another example is shown in Figure A.19. Water (56 ml) was injected from 230 – 248 s. The raw data hardly shows the response of the injection. The spectrum of the first trace shows that there is a large amount of noise in the data. It is assumed that this noise is related to the power supply of the data acquisition device via the mains power.

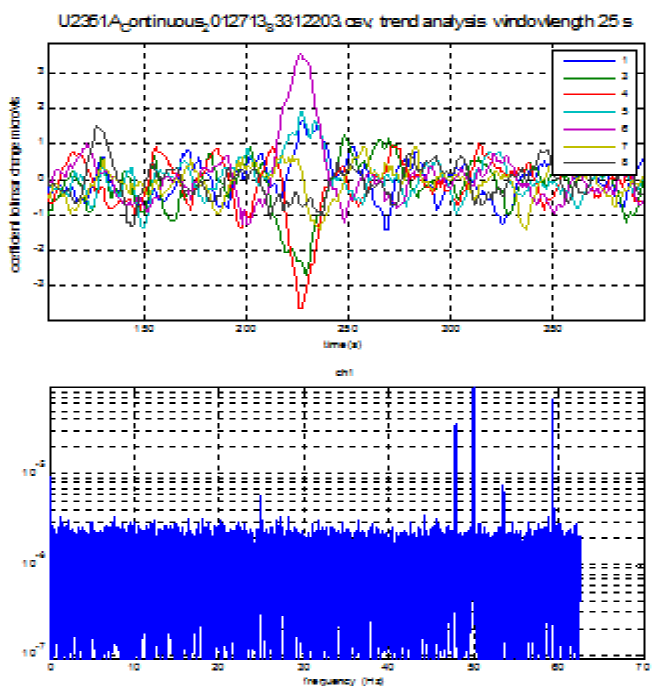

Figure A.19 Raw data, detect levelchange, trendan analysis and spectrum of channel 1 of water injection experiment (mains powered).

A.4.4.2 Measurements using a battery powered DAQ

To assess whether the noise is related to the mains power supply, a few measurements were conducted using a battery instead of a mains power supply. As an example the data, and a trend analysis, as well as a spectrum is shown in Figure A.20. The trend analysis graph shows clearly the anomaly related to the injection (187-212 s). It is seen in the power spectrum that the noise spikes disappeared. So it seems indeed that the noise spikes are indeed related to some interference with the mains power.

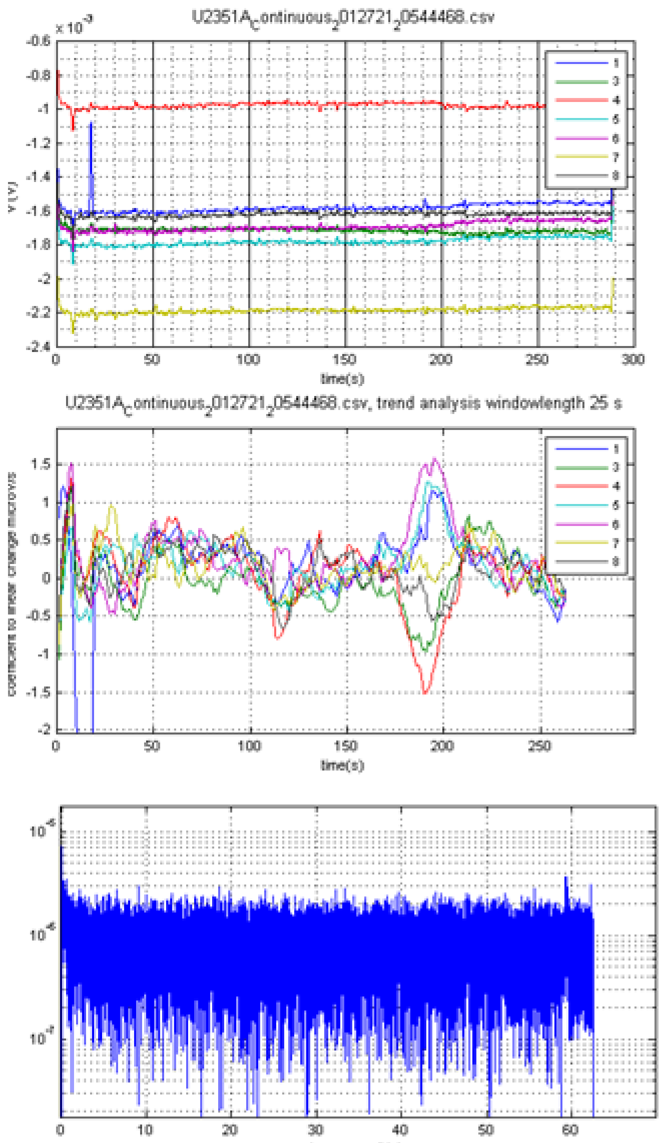

Figure A.20 Data (upper), trend analysis (middle, analysis window 25 s) and spectrum of channel 1 of an experiment employing a battery as power source for the DAQ and injecting 56 ml of water from 187 - 212 s.

The data shown concerns the PMS9000 electrodes. The data from the stainless steel nails does not show the anomaly.

A.4.5 Electrode comparison

Stainless steel electrodes are much cheaper than NPE's. If stainless steel electrodes suffice, this would make the method cheaper. An experiment to compare electrodes was conducted.

Detailed analysis of the (passive) data shows that the NPE's are much more stable than the nails. This is exemplified by Figure A.21. No water was injected for a long period. The signal of the different NPE's is all around 0 V. When magnified, "ideal" straight lines are visible. The signals of the nails have a large bias and instable variations over time. The spectra shown in Figure A.22 show this observation in the frequency domain: the noise floor of the NPE is much (order of two decades) lower than that of the stainless nail.

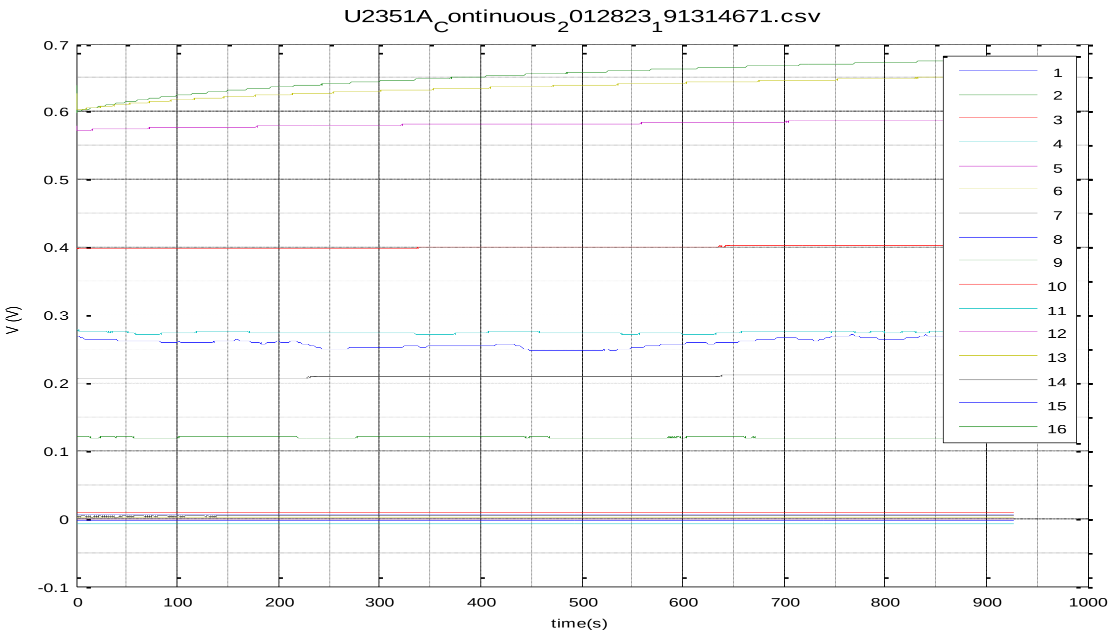

Figure A.21 Measured voltage versus time in a passive mode.

The background noise in the measurements is one of the main imitations of the method. One aspect of the background noise is the position of the electrode either in the vadose zone or the saturated zone. Spectra for both type of electrodes were made positioned in both the unsaturated and saturated zone (Figure A.23).

It is seen that the noise level is considerably lower (2 - 10 times) for the electrodes positioned in the saturated zone.

An explanation for this may be that in the unsaturated zone more chaotic ("randomly" time varying) contact with water is occurring, which leads to more chaotic bias potentials.

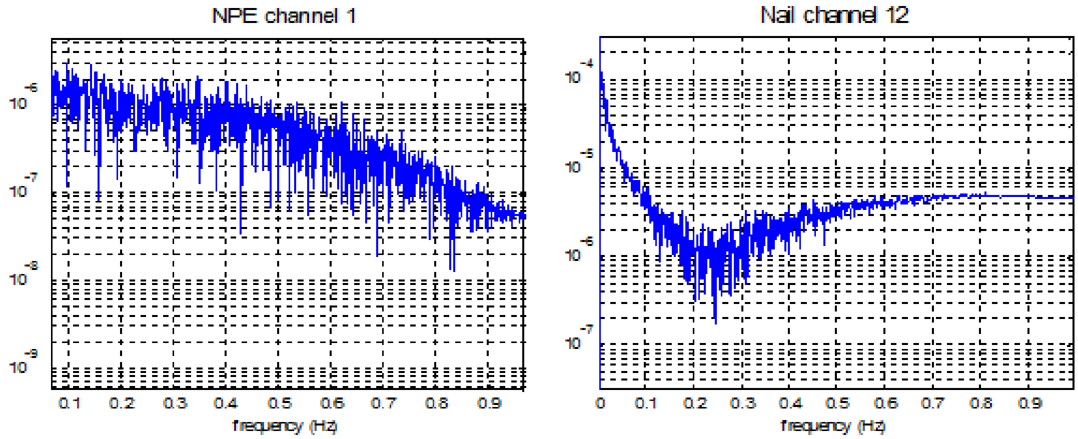

Figure A.22 Spectra: left: Non Polarisable Electrode, right: stainless nail.

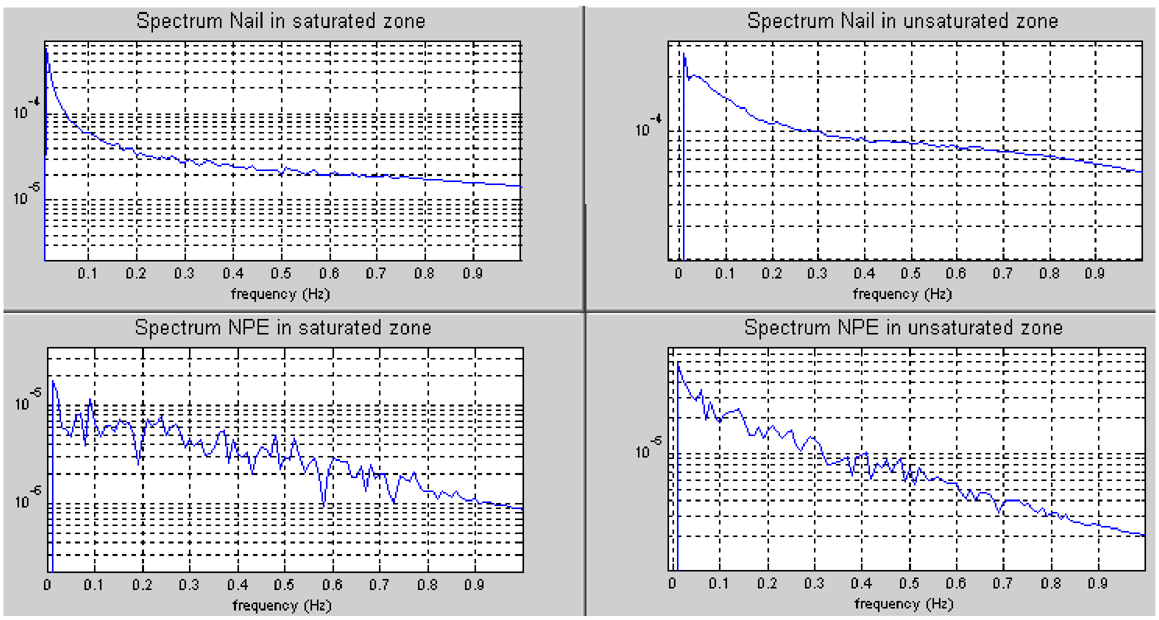

Figure A.23 Spectra of passive measurements (no injection) for nails and NPE's in the saturated and unsaturated zone.

A.5 Proposed measurement layout and processing squeeze

A.5.1 Geological and geophysical modeling of the local situation

If SP is considered to be a useful option in a CO_2 storage project for a specific abandoned well, a sensitivity analysis of the method should be made, taking the local conditions into account. Based on a geological model, parameters must be estimated for the bodies/layers in this model and an estimate of the minimal leakage to be detected must be made.

Using an appropriate Streaming potential code, the leakage can be simulated and the SP-response can be calculated. If the response is higher than a certain, area dependent, threshold value, SP may be a valuable option for the case under consideration.

A.5.2 Measurement layout

If SP turns out to be useful for a certain situation, a location specific design must be made. Firstly an area is defined in which the abandoned well is supposed to be located. Depending on the depth of the well and on the CO_2 storage reservoir a an area around this well is defined. The size of the area should be in the order of the maximum relevant depth.

For this area about a hundred electrode positions are envisaged (10 * 10). Also one, or more, reference electrodes should be placed somewhat outside this area.

The signal of the electrodes should be connected to a hundred channel Single-Ended voltage recorder.

A.5.3 Processing sequence

The noise level is of the same order or even higher than the expected signal level. However, the characteristics of the noise are different from that of the signal. We expect a certain signal related to the flow of water, related to CO_2 escape to have a certain behavior in time and in space.

Thus we can design matched filters for our expected response and thus increase the signal to noise ratio significantly. Matched filtering is a process for detecting a known piece of signal or wavelet that is embedded in noise. The filter will maximize the signal to noise ratio (SNR) of the signal being detected with respect to the noise. The filter can be applied in the time domain and in the X,Y domain.

Different CO_2 escape scenarios will lead to different matching filters. These filters should be applied continuously and checked against threshold values.

Just to indicate what kind of spatial processing technique is meant, an example of data in the tank is given in Figure A.24. The anomaly related to the water injection (450-467 s) is hardly visible in the separate time series. However, the detection of the anomaly is not difficult considering that "something" is happening around the injection time in all curves. Unfortunately there was no time left to develop a processing tool to exploit this feature.

The last few hours of the budget were used to make a (quick and rather dirty) routine that may show this effect somewhat. Figure A.25 shows the result and shows how a cross-channel coherency measure can increase the visibility.

Another example of a trendan result and the q&d channel coherency routine is shown in Figure A.26 (water injection 330 – 340 s). The example shows that the signal can hardly be recognized in the trendan analysis, but that the injection can be inferred from the q&d channel coherency routine.

Another relevant technique can be to apply Independent Component Analysis (ICA) which is used often in electrophysiology to remove eye movement and blink artifacts from EEG recordings (e.g. http://cnl.salk.edu/~jung/artifact.html0).

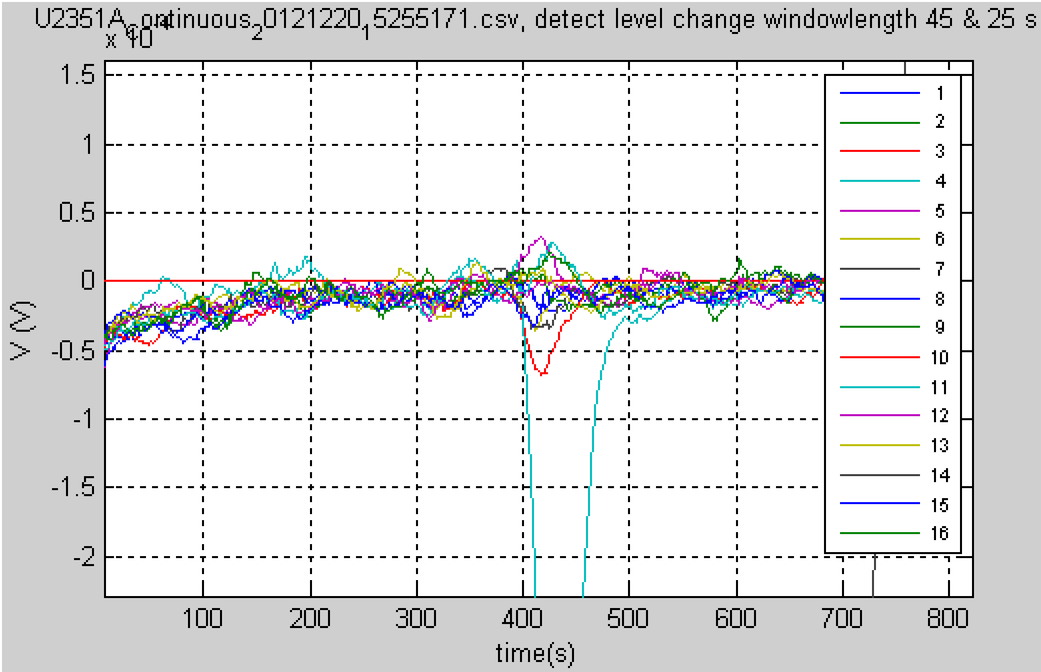

Figure A.24 Example of data in tank (detectlevelchange).

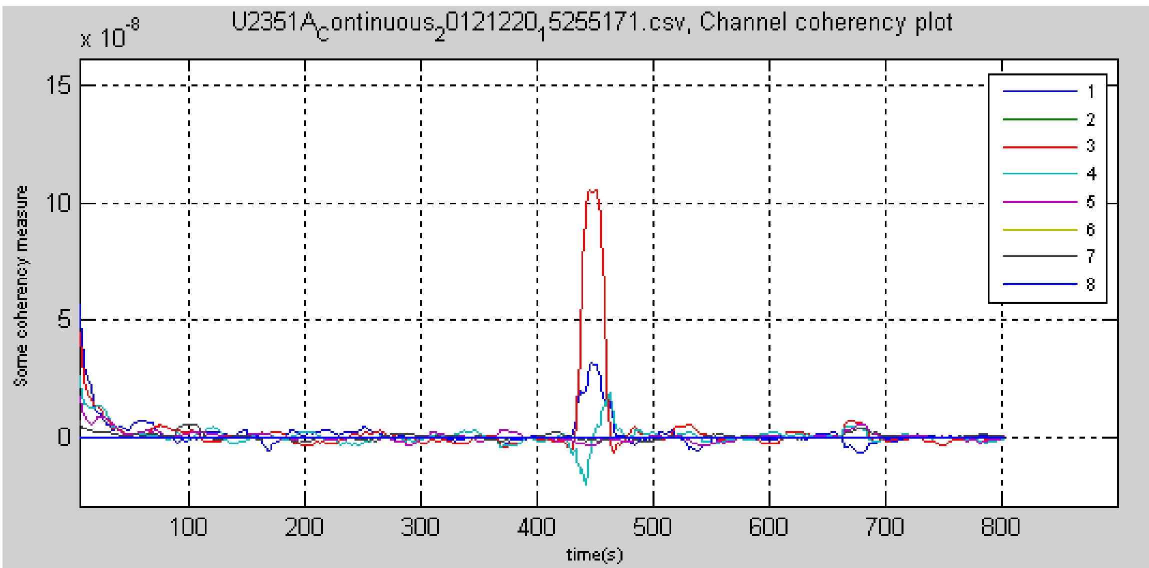

Figure A.25 Example of cross-channel coherency (data from Figure A.24).

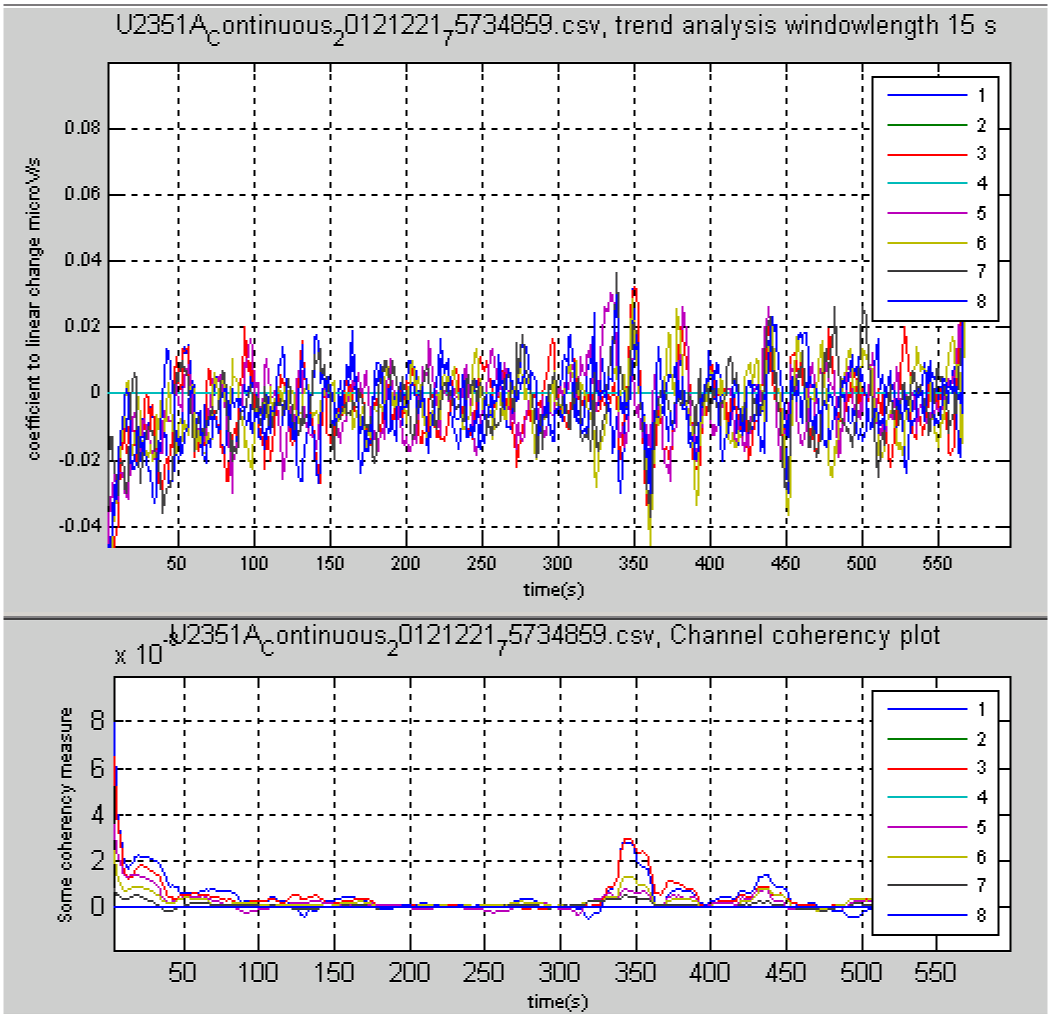

Figure A.26 Example of trendan analysis and "Some channel coherency measure".

ICA-based artifact correction can separate and remove a wide variety of artifacts from potential recordings by linear decomposition. The ICA method is based on the assumptions that 1. the time series recorded (on the scalp) are spatially stable mixtures of the activities of temporally independent cerebral (here: leakage) and artifactual (here: all sorts of noise sources) sources, 2. the summation of potentials arising from different parts of the brain, scalp, and body is linear at the electrodes, and 3. Propagation delays from the sources to the electrodes are negligible.

These assumptions are quite reasonable for SP data. The method uses spatial filters derived by the ICA algorithm. Once the independent time courses of different brain and artifact sources are extracted from the data, artifact-corrected EEG signals can be derived by eliminating the contributions of the artifactual sources.

How to implement these different processing options for a certain acquisition configuration requires further research.

A.6 Conclusions and recommendations

Modeling indicates that recording streaming potentials can be a useful technique to detect leakages from abandoned wells (or other leakages). The main limitation of the method is the amplitude of the SP-signal for realistic conditions. For relative shallow leakages the technique is more sensitive because the distance to the source of the signal decreases and because the volume of displaced water from a leakage increases.

Most field experience exists with relative straightforward 2D-like acquisition geometries for shallow applications. It is expected that the combination of multi-channel recording and processing techniques will push the limit of the lowest detectable signal significantly, thus increasing the depth from which a leakage can be detected and thus increasing the applicability of the technique. This requires further research. This research could be done already in combination with some field test, as the basic principles are not complex and adequately understood.

In the field a grid of electrodes (e.g. 25 electrodes) must be placed around the position of the (abandoned) well. Each electrode measures a voltage relative to a reference electrode, that can be positioned somewhat away from the borehole (so-called single pole configuration) or potential differences between electrodes of the grid can be monitored. Obviously, the implementation on land is easier than off-shore, where a monitoring system (electrodes, cables and a voltage measurement system) must be placed on the seafloor and data transfer to this system must be realized.

Measurements in a tank in the laboratory show that streaming potentials related to injection can be measured. The signal is not stable though and the spatial (lateral) pattern of the amplitudes shows quite some noise.

A.7 References

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