Chair of Drilling and Completion Engineering

Master's Thesis

Test Protocol for the Assessment of Shale as a Barrier in the Decommissioning of Wells

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November 2021

AFFIDAVIT

I declare on oath that I wrote this thesis independently, did not use other than the specified sources and aids, and did not otherwise use any unauthorized aids.

I declare that I have read, understood, and complied with the guidelines of the senate of the Montanuniversität Leoben for "Good Scientific Practice".

Furthermore, I declare that the electronic and printed version of the submitted thesis are identical, both, formally and with regard to content.

Date 05.11.2021

Signature Author
Anastasiia Fedorova

This achievement is dedicated to my esteemed parents and to my beloved husband. Without their continuous support, this thesis would not have been conceivable.

Посвящаю это достижение моим уважаемым родителям и моему любимому мужу, без постоянной поддержки которых написание данной диссертации было бы невозможно. Спасибо!

Affidavit

I declare in lieu of oath that I wrote this thesis and performed the associated research myself using only literature cited in this volume.

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Abstract

Well abandonment is a major challenge in the industry from different perspectives, including costs, the amount of effort and technical difficulties involved with permanent wellbore isolation. In recent years there has been an increased focus on plug and abandonment (P&A) operations. Oil and gas producing companies have an enormous asset of wells to be decommissioned due to mature fields all over the world. The North Sea region is not an exception, as it is the mature play experiencing the wave of well decommissioning activity for the last 15 years.

In the North Sea area, nearly two thousand wells are intended to be plugged and abandoned in the upcoming 5-10 years. P&A of wells of North Sea assets is estimated to reach 50 % of decommissioning costs, including platform removals, which compromise 20 % (Vrålstad, et al. 2018). Operators are searching for new technologies that could minimize expenditures on P&A operations as there are no financial benefits from them.

Well abandonment must fulfil local government regulations, which require long-term well integrity and isolating formations between each other and from the surface. A conventional well decommissioning process might be time-consuming due to remedial cementing, casing milling and casing pulling operations with the rig installation.

The main objective of the master thesis is to investigate the ´shale-as-a-barrier´ (SAAB) technique as the alternative solution to conventional well barriers. Naturally occurring barriers may extend over hundreds of meters along the well and eliminate the need for additional sealing of the annulus. Such a technique could simplify the plugging operations and imply significant cost reductions during P&A operations.

Zusammenfassung

Die Stilllegung von Bohrlöchern ist eine der größten Herausforderungen der Öl- und Gasindustrie. Dies gilt sowohl in Hinsicht auf Kosten und Aufwand, als auch in Hinsicht auf technische Fragestellungen im Zusammenhang mit der Abschottung der Bohrlöcher für unbeschränkte Zeiträume. In den letzten Jahren hat sich der Fokus der Industrie in Richtung permanenter Verfüllung der Bohrlöcher verschoben. Öl- und Gasproduzenten auf der ganzen Welt besitzen eine enorme Anzahl von Anlagen, die sie aus Altersgründen stilllegen müssen. Die Nordsee bildet keine Ausnahme, denn wegen der Betriebsdauer der Felder erfährt sie schon über die letzten 15 Jahre eine Welle der Rückbau- und Außerbetriebnahmeaktivitäten.

In der Nordsee beispielsweise sind für die nächste Dekade Verfüllungsaktivitäten an ungefähr zweitausend Bohrlöchern geplant. Es wird geschätzt, dass die permanente Verfüllung der Bohrlöcher etwa 50 % der Rückbaukosten für die Anlagen in der Nordsee ausmachen werden (Vrålstad, et al. 2018), während dem Rückbau der Plattformen geschätzte 20 % der Kosten zugerechnet werden. Die Öl- und Gasproduzenten suchen nach neuen Technologien um die Kosten der Außerbetriebnahmeaktivitäten zu minimieren, weil sie keinen direkten finanziellen Nutzen davon haben.

Darüber hinaus müssen bei der Verfüllung von Bohrlöchern auch behördliche Regulierungen erfüllt werden. Diese umfassen Aspekte wie das langfristige Abdichten des Bohrlochs, das Sicherstellen seiner Integrität sowie die Isolierung der Formationen von der Oberfläche als auch die Isolierung von Formationen untereinander. Ein konventioneller Rückbau eines Bohrlochs ist ein zeitaufwändiger Prozess dank Arbeitsschritten wie der Ausbesserung der Zementierung, dem Ausfräsen der Rohrtour oder dem Ziehen der Rohrtour mittels einer Bohranlage.

Die Aufgabenstellung der vorliegenden Arbeit umfasst die Fragestellung, ob Schiefergestein als Barriere im Bohrloch alternativ zu konventionellen Barrieren verwendet werden kann. Diese natürlich vorkommende Barriere kann sich über hunderte von Metern entlang des Bohrlochs erstrecken und damit eine zusätzliche des Ringraums unnötig machen; in dem Fall kann die permanente Verfüllung ohne Bohranlage durchgeführt werden. Die Nutzung von natürlich vorkommendem Schiefergestein als Barriere könnte die Rückbau- und Außerbetriebnahmeaktivitäten deutlich vereinfachen und signifikante Kosteneinsparungen ermöglichen.

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Chapter 1 Introduction

1.1 Statement of Problem

All oil and gas wells need to be permanently plugged and abandoned after the end of the operational phase. Well plugging is based on setting several cement plugs in the wellbore to insulate the fluid-bearing formations and to prevent pollution of the environment.

The permanent abandonment is achieved through the deployment of two, as independent as possible, well barrier envelopes. Internal cement plugs deployed within the casing are not sufficient to re-establish the rock-to-rock sealing required by the Regulators. In many cases, the annular sealing is missing, and casing removal or other expensive remediation techniques might be required. It happens when the annular space behind the casing is not cemented, or the cement quality is poor. Under such circumstances, the casing needs to be milled, metal chips have to be removed, and the remaining parts of the casing pulled. These procedures are time-consuming and thus expensive.

Emerging novel technology is the utilization of shale formations to form natural permanent annular barriers. Naturally occurring barriers may extend over hundreds of meters along the well and eliminate the need for man-made interventions to seal off the annulus. According to reported cases of applying ´shale as a barrier´ (SAAB), a sealing formation replaced remedial cementing, casing milling, cutting and pulling operations with the rig installation. SAAB could simplify the plugging operations and imply significant cost reductions during plug and abandonment (P&A) operations.

The potential benefit is not only cost-related because the efforts and costs for every P&A campaign are reduced, but also HSEQ-related as the significantly lower operational complexity reduces potential risks during execution. Environmental aspects play another important role; the CO_2 and overall environmental footprint decrease with reduced operational effort in P&A activities. Considering the big amount of wells that could use SAAB, potential cost savings and HSEQ benefits are enormous.

Shale has all the necessary physical characteristics (e.g. low permeability, non-shrinking, ductile, resistance to chemical degradation, low leak rate) to provide long-term zonal isolation in wells. Signs of a viscoplastic deformation of the rock formation called formation creep are seen in many wellbores. These foamtions may act as well barrier elements by sealing the annular space between uncemented or insufficient cemented casing sections and the formation. Oil and gas companies may abandon those wells with considerable savings if they are able to demonstrate the integrity of that seal to the local Regulator.

Research activities revealed that a shale barrier has properties to self-heal cracks that could occur over time due to lower unconfined strength and friction angle compared to a cement material (Kristiansen, Dyngeland, et al. 2018). This fact is beneficial for the well integrity from the environmental perspective.

By this time, many reported cases are known when creeping shale formations closed the annular gap, which had been poorly cemented or uncemented. However, isolated instances cannot justify the adoption of the SAAB technique for the permanent abandonment of wells in general. Wintershall Dea aims to assess the acceptance of SAAB within the industry and the regulators in the North Sea area and define the main requirements for the shale barrier qualification as the annular seal.

1.2 Scope and Objectives

The main objective is to perform a feasibility study of SAAB application to develop a general procedure for planning and executing decommissioning projects considering the formation barrier.

The general objectives are as follows:

- to perform a literature review of the studies performed so far and of the field experiences;
- to map for the North Sea area the shale characteristics that qualify specific formations as potential SAAB candidates;
- to study technologies to test and examine the presence of a barrier and the bond quality;
- to describe laboratory experiments and tests to be conducted to qualify SAAB.

1.3 Importance of Study

The SAAB project addresses a challenge of the well integrity and the P&A of numerous wells offshore. The technology was applied on several wells within the North Sea area. There are no reported cases of any negative consequences, besides one reported case in which the tertiary recovery can be difficult to implement after wells decommissioning using the SAAB technology within the same field in future. It is seen positively for the reputation of Wintershall Dea to advance SAAB as it will additionally bring the opportunity to collaborate with other companies.

Combining low human exposure and low carbon intensity operations, SAAB may contribute achieving Company's ESG (Environmental, Social and Governance) targets while solving the well integrity challenge in the abandonment of aged assets.

Chapter 2 Wells Plug and Abandonment Legislation

In this chapter, literature review of industry guidance and standards applicable for P&A activities and for SAAB qualification in Europe, specifically in Denmark, Germany, the Netherlands, Norway and the United Kingdom (UK), is outlined.

2.1 General Information

Detailed requirements for permanent abandonment are described in NORSOK Standard D-010 "Well integrity in drilling and well operations" (2021), developed by the Norwegian petroleum industry. According to this standard, four different statuses are known when the well activities are discontinued:

- Suspension of well activities and operations due to waiting on weather or equipment, workover operations, etc. The well activities are paused without removing the well control equipment pertaining to wells under construction or intervention.
- Temporary abandonment of wells which are under specific conditions, e.g. they had a long shutdown, are waiting on a workover, waiting on field development or re-development. The well control equipment is removed with a view to later re-entry or permanent abandonment.
- Permanent abandonment of a section in a well (sidetracking, slot recovery) to drill a new wellbore from the main wellbore.
- Permanent abandonment of wells to never be re-used or re-entered.

Wells permanently plugged and abandoned, depending on the causes for P&A, are divided into four categories (РД 08-347-00 2001):

I. Wells fulfilled their purpose:
   a) production wells that reached the lower limit of flow rates due to water flooding or reservoir depletion, and it is not economically viable to produce hydrocarbons from this well;
   b) injection wells that reached the lower limit of injectivity rates;
   c) observation, appraisal or injection wells in the absence of the need for their further use.
II. Wells abandoned due to geological causes:
   a) dry wells that do not give an influx;
   b) wells that do not tap reservoirs.
III. Wells abandoned due to technical causes:

a) wells with leakage of the production casing as a result of its corrosion wear due to prolonged operation in an aggressive environment;

b) wells having been subjected to accidents and complications with the loss of the borehole;

c) wells destroyed due to natural disasters (earthquakes, landslides);

d) wells drilled with unacceptable deviations from the well target.

IV. Wells abandoned due to technological, ecological and other causes:

a) wells that have been completed and are not suitable for operation due to the non-compliance of the strength and corrosion-resistant characteristics of the casing with the actual conditions;

b) wells located in protective and buffer zones, restricted areas, according to the requirements of environmental authorities;

c) the bankruptcy of the company, lack of financing of the well construction, termination of company's activities.

The most common examples in each category are presented, and the list can be enlarged.

The major scope of wells P&A is to provide the well integrity of the abandonment by assuring that there are no fluid communications from any permeable fluid-bearing formation to the surface via any casing annulus. For this purpose, a system of one or more barriers called the well barrier envelope is installed inside the well. As a general rule, two independent well barriers are required. Well barriers extend across the full cross-section of a well, comprise all annuli and insulate in both directions vertically and horizontally (International Association of Oil and Gas Producers (IOGP) 2017).

The primary well barrier hinders flow from a source. The secondary well barrier is the backup barrier that protects from flow in case of a failure of the primary barrier. The principle of the two-barrier philosophy is shown in Figure 1.

The typical example of the well barrier schematic used at Wintershall Dea is shown in Figure 2. This colour coding largely applied in the oil and gas industry consists of blue and red colours. The blue colour designates primary barrier elements, and the red colour designates secondary barrier elements.

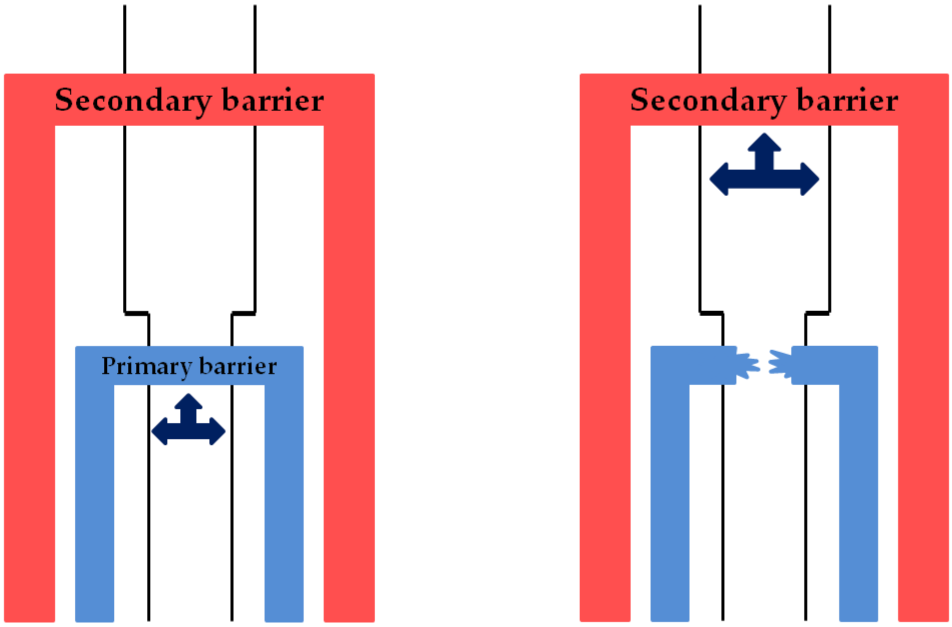
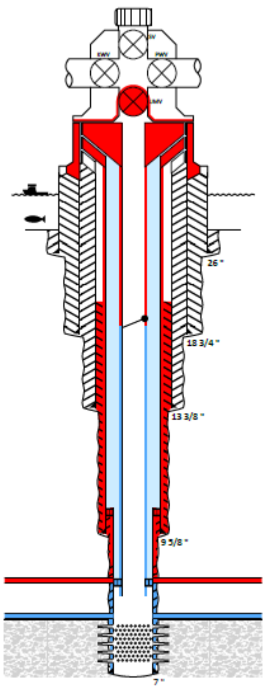


Figure 1: Two-independent barriers philosophy [adapted from (Fredagsvik 2017)].



Primary barrier elements		
Element	**Qualification**	**Monitoring**
Collapsed shale	Formation test, job performance or bond log	B-annulus pressure
Tubing	Pressure test to xxx Bar	A-annulus pressure
Production packer	Pressure test to xxx Bar	A-annulus pressure
Production liner	Pressure test to xxx Bar	B-annulus pressure
Production liner cement	Formation test, job performance or bond log	B-annulus pressure
Annulus fluid	Fluid sg control based on expected pore pressure	Active pit level / in-out volume balance
Secondary barrier elements		
Element	**Qualification**	**Monitoring**
Collapsed shale	Formation test, job performance or bond log	B-annulus pressure
Surface x-mas tree	Pressure test to xxx Bar	Periodic testing
Tubing hanger	Pressure test to xxx Bar	A-annulus pressure
Tubing	Pressure test to xxx Bar	A-annulus pressure
Wellhead	Pressure test to xxx Bar	External observation
Casing hanger	Pressure test to xxx Bar	A-annulus pressure
Liner top packer	Pressure test to xxx Bar	A-annulus pressure
Production casing	Pressure test to xxx Bar	B-annulus pressure
Production liner	Pressure test to xxx Bar	B-annulus pressure
Production casing cement	Formation test, job performance or bond log	B-annulus pressure
Production liner cement	Formation test, job performance or bond log	B-annulus pressure

Healthy well, no or minor issue

Note:

Figure 2: Well barrier schematic used at Wintershall Dea.

The potential materials for the well barrier are listed and discussed in “Guidelines on the Qualification of Materials for the Abandonment of Wells” (Issue 2, 2015) issued by Oil and Gas United Kingdom (O&G UK). These are as follows:

- Cements, ceramics;

- Grouts;
- Thermosetting polymers and composites;
- Thermoplastic polymers and composites;
- Elastomeric polymers and composites;
- Formation;
- Gels;
- Glass;
- Metals;
- Modified in-situ materials.

The present master thesis focuses on the 'formation material' class only. The following conclusions have been made regarding this well barrier material.

SAAB might be used only for permanent well abandonment, slot recovery and sidetracking purposes.

Well P&A operation with the SAAB concept shall be planned for the reason that it takes time to form the annular barrier. Optimally the well should be designed, constructed and maintained so that they can be efficiently abandoned with the SAAB technology. From this perspective, the formation type barrier can be suitable mostly for the first category of wells mentioned above, wells that fulfilled their purpose.

Finally, the movement of shale formations is not predictable, and this technology has been understudied yet. It is therefore preferred to elaborate a contingency plan with the deployment of alternative well barrier elements to isolate the annuli.

It is quite important to review state regulations and international requirements to get acquainted with existent requirements for the qualification of SAAB.

2.2 The North Sea Region Legislation

The specificity, importance and approach towards decommissioning and P&A activities vary significantly by country. While some countries possess detailed and specific legislation and requirements, other countries only go as far as setting the goals of the P&A operations.

This master thesis focuses on North East Atlantic region countries, particularly Denmark, Germany, the Netherlands, Norway and the UK, in which Wintershall Dea operates (Fig. 3).

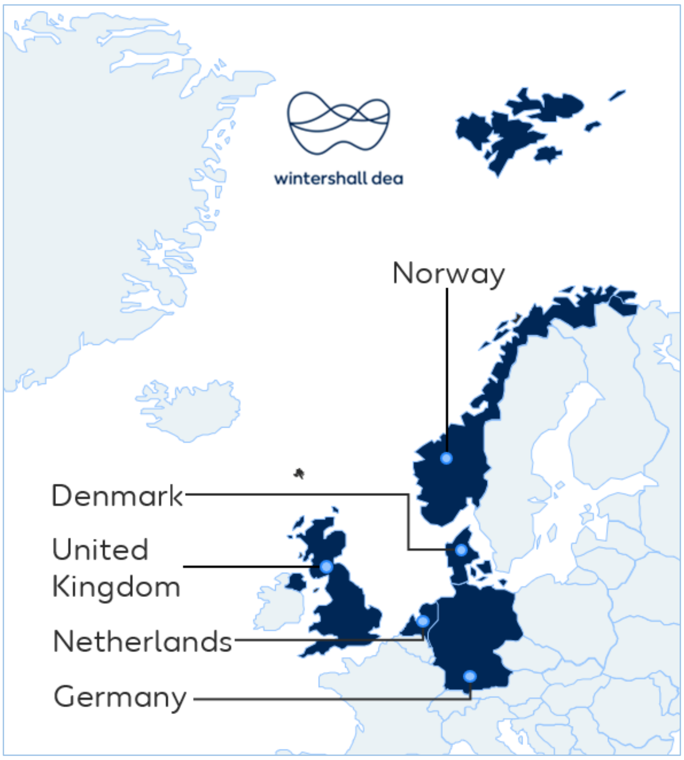


Figure 3: The North East Atlantic region.

Decommissioning and P&A activities are regulated by the government authorities; local regulations precede international legislation. Local regulations have mostly changed considerably over the past years, introducing stringent environmental protection controls and concluding the minimum requirements. Some operators have their own more stringent internal requirements and tend to follow them where the regulatory authorities do not provide sufficient requirements (Khalifeh M., Saasen A. 2020).

It is worth mentioning that often drilling contractors and operators often partially or fully follow internationally recognized organizations, e.g. Norsk Sokkels Konkuranseposisjon (NORSOK), Det Norske Veritas (DNV), when elaborating their policies and procedures for P&A operations. The standards and procedures produced by these bodies have been developed through the years from lessons learned, incidents and the introduction of new technologies and techniques (International Association of Oil and Gas Producers (IOGP) 2017).

The standards and guidelines related to the qualification of shale as an annular barrier and issued by these organizations are discussed further.

2.2.1 Denmark

The main framework act regulating the Danish upstream oil and gas activities is the Danish Subsoil Act (DSA) of 2007 (amended in 2011). The DSA governs the decommissioning of oil and gas facilities and installations. Also, it provides to licensees the requirements stipulated by the Danish Energy Agency (DEA) for contents of decommissioning plans. These requirements are fully covered in Section 32a 'Guidelines on decommissioning plans for offshore oil and gas facilities or installations' of the DSA (Act on Danish subsoil exploitation (No. 960 of 2011)). The decommissioning and P&A ought to be planned and submitted to the DEA no later than two years before the commencement of decommissioning activities.

The well closure is the part of decommissioning which includes the following operations: well closure, insulation, plugging, integrity test, cutting of guiding pipe or well equipment, remediation of the drilling site. The Danish Working Environment Authority (DWEA) and the Danish Environmental Protection Agency (DEPA) are the regulatory authorities involved before any approval of decommissioning plans at this stage.

It is important to note that the guidelines of Section 32a shall be applied in combination with other guidelines, e.g. "Guidelines for Drilling – Exploration" (DEA 2009), "Guidelines on Security and Insurances" (DEA 2018) and "Guidelines on Technical Capacity" (DEA 2018).

In 'Wells Abandonment' section of "Guidelines for Drilling – Exploration", requirements regarding internal barrier, annular barrier, casing stump, plugging and verification of the well barriers are reported (Danish Energy Agency (DEA) 1988 (2009)).

The guidelines guide for well abandonment (Danish Energy Agency (DEA) 1988 (2009))., and state that:

> *A well shall be plugged such that it is ensured that no fluid or flow through the hole and no communication from downhole formation to the seabed via any casing annulus is possible. To this end, multiple plugs shall be placed. The total weight of cement plugs and fluid between the plugs shall ensure that the system is in balance with any pressure which may develop in the borehole.*

Plugs shall be tested with enough differential pressure for sufficient time to detect leaks or mechanical failures of the plug. Additionally, the top of cement plugs shall be spaced by load testing.

In general, it is allowed to utilize the cement barrier that can be in combination with a mechanical plug. However, there is no mention of the formation type barrier. As a result, the application of SAAB technology turns impossible within Denmark.

2.2.2 Germany

The main legislative act regulating the exploration of oil and gas is Bundesberggesetz (BBergG) – the Federal Mining Law of 1980 (last amended in 2017). The Federal Mining Law is not exhaustive and is further accompanied by a number of ordinances, standards and guidelines on technical and procedural issues.

P&A procedure and design should be prepared in accordance with these following regulations, functional requirements and standards:

- Tiefbohrverordnung BVOT Land Niedersachsen, 2006 – the Deep Drilling Ordinance.

- Bergverordnung für das Gebiet der Küstengewässer und des Festlandsockels (Offshore-Bergverordnung – OffshoreBergV), 2016 (BGBl. I S. 1866) – the Mining Ordinance for the Area of Coastal Waters and the Continental Shelf (Offshore Mining Ordinance – OffshoreBergV).
- BVEG Technische Regeln Bohrungsintaegritaet, 2017 – BVEG Technical Standard "Borehole Integrity".
- Guideline of the Oberbergamt in Clausthal-Zellerfeld about abandoning boring holes, 1998.

The P&A operational plan should be approved by the State Office for Mining, Energy and Geology (LBEG), and it includes the following information (not limited to):

- the reason for the well P&A;
- the depth areas intended for the plug sections;
- the intended filling materials;
- if necessary, specification of the deflection levels and areas in which drilling difficulties have arisen and which are important for ensuring the P&A objective.

This guideline of the Oberbergamt in Clausthal-Zellerfeld applies to the complete and partial P&A of boreholes within the scope of the Deep Boring Ordinance – BVOT. The P&A work is subject to the operating plan obligation in accordance with Section 51 (1) of the Federal Mining Law. An exemption from the operating plan obligation in accordance with Section 51 (3) is not possible.

It should be mentioned that the salt creeping formation is acceptable to be an annular barrier element in combination with cement plugs within this guideline. The length requirements are indicated in Figure 4. A continuous cement plug is dispensed within thick salt layers. In the overlaying and underlaying areas, a cement plug section of at least 100 m in length in salt and 50 m in the non-salt formations must be placed

Technical Standard "Borehole Integrity" is supplementary to existing legal and regulatory requirements, technical codes and internal company specifications. The entire life cycle of a borehole, consisting of design, production, operation and startup, is covered.

Borehole barriers must be maintained throughout the life cycle of a borehole must fulfil the following criteria:

- withstand expected maximum combined loads;
- remain functional under the conditions (pressure, temperature, mechanical and chemical stresses) that can act on them;
- be verifiable through scheduled initial inspections and recurring re-inspections and tests (BVEG 2017).

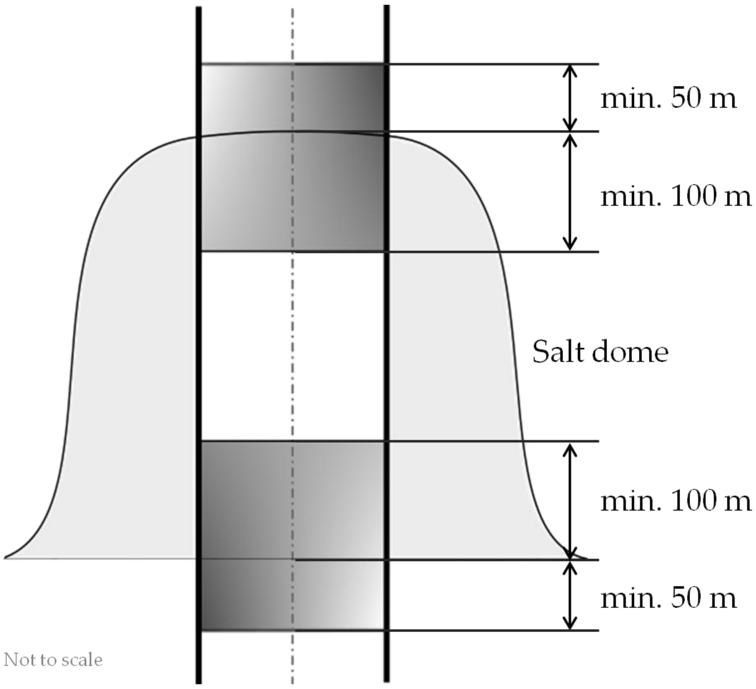


Figure 4: The length requirements for salt external barrier and for cement plugs inside a casing (Guideline of the Oberbergamt in Clausthal-Zellerfeld about abandoning boring holes 1998).

2.2.3 The Netherlands

The framework act regulating the oil and gas industry is the Dutch Mining Act of 2002 (last amended in 2020) which consists of three levels:

- the Mijnbouwwet, 2002 – the Mining Act of the Netherlands itself;
- the Mijnbouwbesluit, 2002 – the Mining Decree;
- the Mijnbouwregeling, 1983 – the Mining Regulations.

In § 5.2.3 and § 5.2.4 of The Mining Decree, the procedure for decommissioning of mining installations is located above and below surface water, respectively. For well decommissioning, Article 72 (§ 5.3.1) states that when decommissioning a well measures should be taken to prevent damage and the mineral-bearing strata and mineral deposits have been sealed in a water-tight manner (Mining Decree of the Netherlands 2002).

Under Article 8.2.4.2 of the Mining Regulations, a work programme for well P&A is required to be submitted to the Inspecteur-Generall der Mijnen at least four weeks before the commencement of activities. Article 8.2.4.1 determines the work programme, which consists of details on the well location, reasons for decommissioning the well, and an explicit description of the well to be decommissioned (Mining Decree of the Netherlands 2002).

Part 8.5 of the Mining Regulations covers the requirements for well P&A. It is established in Article 8.5.1.2 that another isolation device, which is equivalent to a 'cement plug', may be used (Mining Regulations of the Netherlands 1983). And it considers the formation barrier possible in this case. It is also established that every seal used in the well shall be durable and complete.

The main qualification for the annular barrier is to withstand testing, which is described in Article 8.5.2.1 (Mining Regulations of the Netherlands 1983):

> *1. Each seal of a well that is decommissioned shall be tested employing:*
>
> *a) A weight test of at least 100 kN (10,250 kg);*
>
> *b) Test pressure of at least 50 times 100.000 Pa (50 bar) for 15 minutes;*
>
> *c) Negative pressure differential in the well whereby it is established that no fluid from the reservoir flows into the well.*
>
> *2. The seal shall withstand the tests well.*

Requirements regarding the length of annular sealing are prescribed in Article 8.5.2.5 (Mining Regulations of the Netherlands 1983):

> *1. In every annular space between the series of the casing, a seal shall be fitted over a length of at least 100 metres from the shoe of the casing directly preceding it.*

In the Netherlands, thirteen companies have a license to explore for and produce gas. These oil and gas companies explore possible gas reserves underground and under the North Sea and ensure the production of natural gas after the exploration stage. These companies shall fulfil the standards issued by Netherlands Oil and Gas Exploration and Production Association (NOGEPA). As mentioned above, any material besides cement can be utilized if these materials comply with the specific requirements given in NOGEPA Standard Nr. 45 (2021). This standard introduces more stringent criteria for annular barriers

2.2.4 Norway

The Norwegian Petroleum Directorate (NPD) is the regulatory authority for the Norwegian sector of the North Sea area and cooperates with the Ministry of Petroleum and Energy (MPE) of Norway.

The decommissioning plan shall be submitted to the MPE not earlier than five years and not later than two years before the license expiration date or when the operation of a facility is supposed to be broken off permanently.

The cessation procedure of petroleum activities is exposed in Chapter 5 of the Norwegian Petroleum Activities Act 1996 and Chapter 6 of The Regulations Relating to Conducting Petroleum Activities (The Activities Regulations, last amended in 2020).

Section 47 of the Regulations Relating to Design and Outfitting of Facilities, etc. in the Petroleum Activities (The Facilities Regulations, last amended in 2015) states further detailed requirements for formation barriers:

- The barriers shall be designed and positioned in a manner that they provide the well integrity for the longest period.
- The well barriers shall be designed in a manner that their performance can be tested and verified (Petroleum Safety Authority Norway 2015).

The Activities Regulations state that to fulfil the requirements regarding well barriers, the NORSOK D-010 standard 'Well integrity in drilling and well operations' (last amended in 2021) should be followed. Mainly, operators tend to follow NORSOK D-010 as there is detailed description with requirements and review of possible scenarios in wells P&A operations.

2.2.5 The United Kingdom

Offshore oil and gas in the United Kingdom Continental Shelf (UKCS) is controlled through the Petroleum Act of 1998 (last amended in 2016). The work programme for the P&A activities must be submitted to the Secretary of State in advance.

Part IV, and more specifically Regulations 13, 15 and 16, of The Offshore Installations and Wells (Design and Construction, etc.) Regulations 1996 (SI 1996/913) are relevant to well P&A activities (UK Public General Acts 1996).

> *Regulation 13: 1. The well-operator shall ensure that*
>
> *a) there can be no unplanned escape of fluids from the well;*
>
> *b) risks to the health and safety from it or anything in it, or in strata to which it is connected, are as low as is reasonably practicable.*
>
> *Regulation 16: The well-operator shall ensure that every part of a well consists of material that is sufficient for achieving the purposes described in Regulation 13 (1).*

On the grounds that the government regulation of the UK consists of the minimum requirements for well P&A activities, operators follow the guidelines produced by O&GUK.

2.3 National Regulations

2.3.1 Netherlands Oil and Gas Exploration and Production Association (NOGEPA)

In the Netherlands, the association of companies licensed to research and explore oil and gas in the North Sea is called NOGEPA. This organization produces safety standards of the operations and related safety training.

NOGEPA proposes standard Nr. 45 "Decommissioning of Wells" (last amended in 2021) with specific and detailed requirements for sealing mobile formations denoted in Chapter 7 of NOGEPA Standard Nr. 45.

The qualification of a formation seal in a well should include:

1. *Proof that the formation has the required fracture strength to withstand the anticipated future pressures, in present or adjacent wells, by means of a pressure test.*

2. *Verification that the length of the seal exceeds 50 m (or the Caprock thickness, if less), whereby the quality of the seal must be at least equivalent to that of a good cement seal. Two independent logging tools (e.g. an acoustic cement bond tool and an ultrasonic circumferential cement evaluation tool) should be run to confirm the good quality of the bond between the casing and the formation. An experienced specialist should interpret and document the logging results using formation-specific parameters.*

3. *Validation that the log response can be interpreted as not leaking at the maximum anticipated pressure. This can be achieved by a pressure test between perforations that are (less than) 50 m apart. Once the quality of the formation sealing has been established on a few wells, this validation activity could be omitted (NOGEPA 2021).*

2.3.2 Norsk Sokkels Konkuranseposisjon (NORSOK)

The NORSOK standards are developed by the Norwegian petroleum industry to ensure adequate safety, value adding and cost effectiveness for existing and future petroleum industry developments in Norway.

The NORSOK D-010 standard is to be known as a standard that has the qualification requirements for the creeping formation barriers. Since shale could be a natural barrier was discovered on the Norwegian Continental Shelf (NCS), NORSOK has started developing requirements and a qualification procedure for formation barriers.

The standard states that the suitability of the selected plugging material shall be verified and documented and that degradation of the casing should be considered. The guidelines do not specify that the plugging material must be cement, rather than a permanent barrier should have the following characteristics listed in Table 1.

Property	**Requirement**
Long term integrity	Key integrity indicators like compressive and tensile strength, permeability and Young's modulus should when measured over longer period, not indicate a deteriorating long-term trend. If such a trend is observed the test should continue to determine the final stable value.
Permeability	Water permeability smaller or equal to 5 µD, or smaller or equal to 1000 times the formation permeability whichever is greatest. Alternatively, the zonal isolation material shall as a minimum have a combined permeability and length such that its ability to prevent fluid migration is as good or

	better than the cap rock it replaces.
Radial shrinkage	For open hole plugs or open hole Well Barrier Elements (WBEs): low shrinkage. For internal, cased hole WBEs: long-time positive linear expansion.
Mechanical loads	For WBEs exposed to loads outside relevant knowledge/experience envelopes (geothermal, injection, high depletion, high pressure test etc.), Finite Element Analysis (FEA) should be performed and a 40 % safety factor in each individual load case should be achieved.
Chemical stability	Withstand exposure to chemicals or substances that can exist without substantially affecting required integrity (hydrogen sulphide H_2S, carbon dioxide CO_2, brines, hydrocarbons).
Bonding on tubular	Shall bond properly to uncoated and de-greased steel or other tubulars in contact with it where bonding is required. If bonding cannot be achieved, the material shall be proven to have a compensating mechanism (expansion) that provides a hydraulic seal to casing and any exposed formation in contact with it.
Effect on tubular integrity	Shall not detrimentally affect properties of tubular in contact with barrier material.

Table 1: Well barrier material requirements [Table 26 (NORSOK 2021)].

See Section 10 “Abandonment activities” of the NORSOK D-010 standards for further details.

The external formation barrier shall be used in combination with the internal cement or mechanical plugs. The number of well barrier envelopes depends on the source of inflow [See Table 1 in NORSOK D-010 (2021)]. Each plugging material has its own requirements, which shall be fulfilled. Nevertheless, the thesis focuses on the requirements for creeping formation as external Well Barrier Element (WBE) provided in EAC Table 52, C52 of the NORSOK D-010 standard (Appendix A).

The main requirements are highlighted below:

- the minimum length shall be 30 m MD for a qualified WBE and 2x30 m MD if it is a part of the primary and secondary well barrier;
- two independent logging measurements shall be applied, and logging measurements shall be implemented azimuthally;
- the element shall be capable of providing an eternal hydraulic pressure seal;

- the minimum formation stress at the base of the element shall be sufficient to withstand the maximum pressure that could be applied (NORSOK 2021).

2.3.3 Oil and Gas UK (O&G UK)

O&GUK are the independent legislative body for the UK offshore oil and gas industry and operates with the government, companies across the sector and stakeholders to address the issues related to the oil and gas sector.

O&GUK have produced “Guidelines for the Suspension and Abandonment of Wells” (Issue 4, 2012) and the updated version “Well Decommissioning Guidelines” (Issue 6, 2018). The guidelines are suitable for exploration, appraisal and development wells and state that each well is unique and the approach for the well P&A should be considered on an individual basis. O&GUK has published “Guidelines on Well Abandonment Cost Estimation” (Issue 2, 2015) as well, where the principles and practices provide a common approach to estimating field-wide well decommissioning costs.

In addition, O&GUK has published “Guidelines on the Qualification of Materials for the Abandonment of Wells” (Issue 2, 2015).

The placement and the sealing capability of a permanent barrier should be ensured through verification methods. Specific guidelines on verification methods, specifically inflow testing, are prescribed in “Well Life Cycle Integrity Guidelines” (Issue 4, 2019).

The requirements for the formation barrier intercept the requirements provided in NORSOK D-010 (2021). For instance, the main characteristics of a barrier material coincide and are listed below:

- low permeability – to prevent the flow of fluids through the bulk material;
- provide an interface seal – to prevent the flow of fluids around the barrier, the material provides a seal along the interface with adjacent materials such as steel pipe or rock, and risks of shrinkage and de-bonding are to be accounted;
- the barrier material must endure at the intended position and depth in the well;
- long-term integrity – long-lasting isolation characteristics of the material, not deteriorating over time, risks of cracks and de-bonding over time are to be considered;
- resistance to downhole fluids (hydrogen sulphide H_2S, carbon dioxide CO_2, hydrocarbons, brine) at foreseeable pressures and temperatures;
- mechanical properties suitable to accommodate loads at foreseeable pressures and temperatures (Oil & Gas UK 2015).

In Section 7.15 ‘Sealing Formations’ of “Guidelines for the Suspension and Abandonment of Wells” (Issue 4, 2012) it is outlined the requirements for permanent formation barriers, which are the following:

1. *Proof that the formation has the required fracture strength to withstand the anticipated future pressures.*

2. *Verification that the length exceeds 100 ft per barrier, whereby the bond log response must be equivalent to good cement or better. Each well requires two independent logging tools (e.g. a sonic cement bond tool and a circumferential cement evaluation tool) to be run to confirm the bonding between the casing and the formation with no channels.*
3. *Validation that the bond log response can be interpreted as not leaking at the anticipated future pressures. This can be achieved through a pressure test between 100 ft spaced perforations.*
4. *The verification and validation should be documented (Oil & Gas UK 2012).*

In Section 3.4.2 'Sealing Formations' and Section 4.3.1 'Verifying Sealing Formations' of the newer version "Well Decommissioning Guidelines" (Issue 6, 2018), there is no certain length of the barrier mentioned. It is said that the cumulative length of the resulting seal against the casing shall be adequate to prevent the flow of the present fluids at the maximum anticipated pressures, and the seal formation should be impermeable and have adequate strength. These properties should be lasting at the prevailing conditions.

The main difference is that "Guidelines on the Qualification of Materials" provide general considerations for new technology qualification. This concept is comprehensive and accommodates all aspects of the new technology. It is said that the qualification should be based on the following philosophy (Fig. 5).

- The qualification process should be developed on a systematic approach.
- Potential failure modes should be defined, and their relevance should be identified based on their risk, i.e. the combined probability and consequences of a failure mode occurring.
- A program of measurements and tests should be devised – an 'experimental work plan' to evaluate the suitability of the material for its use as a barrier, considering to the materials in contact with the barrier.
- Theoretical analysis and calculations should, when practical, be used as the main tool to record the fulfilment of the specifications and margins against failure. Tests should verify theoretical calculations.
- The experimental work plan should be the principal means of demonstrating and documenting that manufacture and deployment (Oil & Gas UK 2015).

The experimental work plan is provided in Appendix B with the full lists of tests on core or cutting samples required to qualify the formation as an annular permanent barrier.

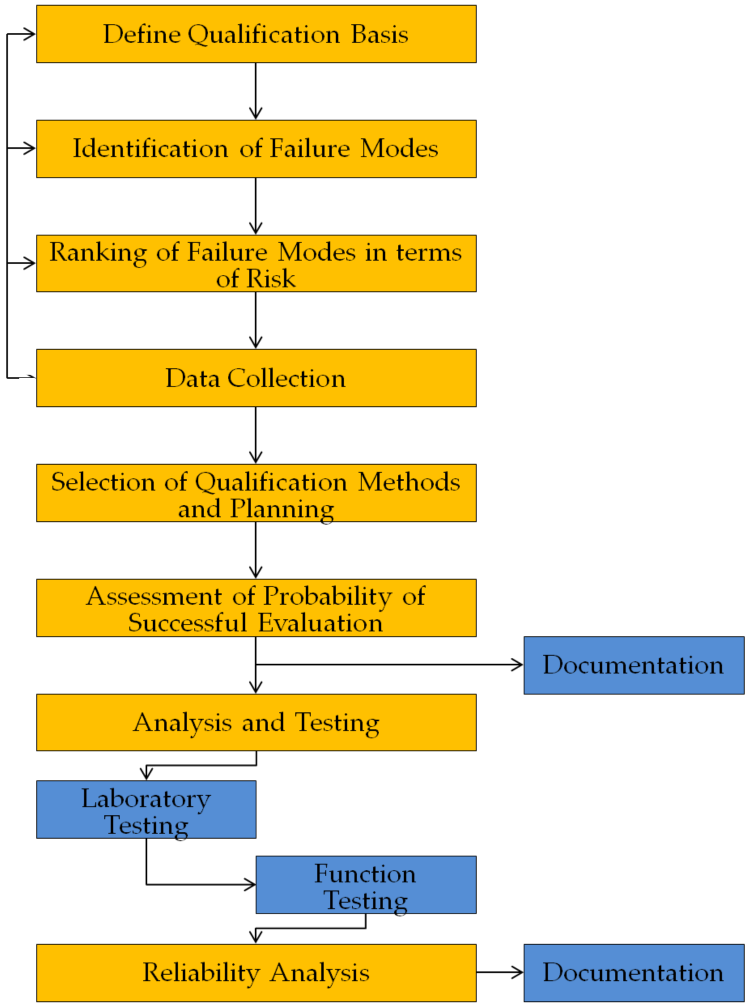


Figure 5: Process for the qualification of new technology (Oil & Gas UK 2015).

2.4 International Regulations

2.4.1 The International Organization for Standardization (ISO)

The International Organization for Standardization (ISO) is an independent, non-governmental international organization with a membership of 165 national standards bodies.

ISO issued a standard ISO 16530-1 "Petroleum and natural gas industries – Well integrity – Part 1: Life cycle governance". It is said that the document applies to any well or group of wells without consideration of their age, location or type.

This standard includes the 'Abandonment Phase' defining the requirements for permanently abandoning a well. It is worth mentioning that the standard provides the full list of factors that affect well barriers and should at least be considered.

Article 11.4.2 'Well Material Selection and Qualification' refers to NORSOK D-010 and O&GUK guidelines.

2.4.2 Det Norske Veritas (DNV)

The DNV group was founded following the merger between the classification societies DNV and Germanischer Lloyd (GL) in September 2013.

DNV is a free-standing, autonomous and independent foundation to safeguard life, property and the environment. DNV delivers world-renowned testing, certification and technical advisory services to the energy value chain, including renewable energy sources, oil and gas, and energy management.

DNV suggests a risk-based perspective to regulate P&A, while the conventional way is from a prescriptive point of view. DNV has issued "RP-E103 – Risk-based abandonment of offshore wells". DNV proposes that the individual approach is required to P&A operations for each well on the ground that wells may not need the same number, type and size of barriers to be safe and protect the environment.

A permanent well barrier may compose of any material or combination of WBEs supposing that it fulfils the following functionalities:

- withstand the maximum anticipated combined loads to which it can be subjected;
- function as intended in the environments (pressures, temperature, fluids, mechanical stresses) that can be encountered;
- prevent unacceptable hydrocarbon flow to the external environment (DNV 2016).

The advantage of this approach is quantitative risk calculations to evaluate the suitability of the final abandonment design. This approach allows to identify the suitability of SAAB technology and reduce the consequences of SAAB failures.

2.5 Summary

The current regulations and standards are not aligned on the applicability and qualification of the SAAB technology. The SAAB technology is not applicable in Denmark and Germany in the current regulatory framework. Nevertheless, in Germany, a salt formation as an external well barrier is acceptable, and still, the requirements are not detail-oriented regarding the barrier properties and its qualification.

The new technology is fully covered by the current NOGEPA Standard Nr. 45, NORSOK D-010 standard and O&G UK guidelines. As a result, companies in the Netherlands, Norway and the UK can apply the SAAB technology directly as long as it has been proven to work safely through pilot-wells and testing.

It is worth mentioning that some major oil and gas companies have issued their manuals with requirements for sealing formations.

Chapter 3 Shale Formation as a Barrier

The chapter will mainly focus on qualified formations in the North Sea, shale mineralogy, properties and the main parameters influencing the non-linear relationship between strain and stress.

3.1 Definition of Shale

Sedimentary rocks, particularly terrigenous clastic sediments, are composed of fragments that result from the weathering and erosion of older rocks. A convenient division of all sedimentary rocks is shown in Figure 6 (Nichols 2009). Moreover, they are classified according to the grain sizes of clasts present and the composition of the material. The most widespread grain size classification of particulate matter is the Wentworth Scale shown in Figure 7.

Terrigenous clastic sedimentary rocks are composed of mudrocks, sandstones and conglomerates. Mudrock is a fine-grained terrigenous clastic sedimentary rock that forms from the compaction of silt and clay-size mineral particles (Fig. 7). Silt is defined as the grain size of material between 0.0039 and 0.063 mm in diameter. Clay consists of the finest grade of clastic sedimentary particles, which are less than 0.0039 mm in diameter.

The term shale is sometimes applied to any mudrock, e.g. by drilling engineers, but it is best to use this term only for mudrocks that show a fissility, which is a strong tendency to break in one direction along laminations, parallel to the bedding (Nichols 2009).

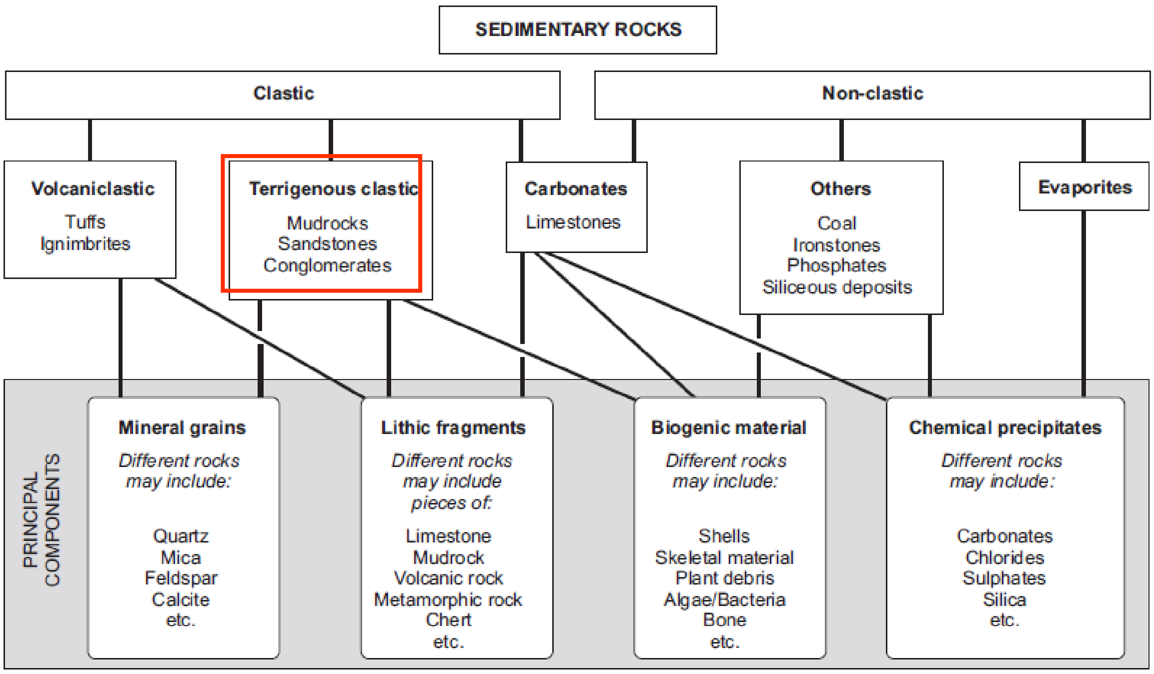


Figure 6: A classification scheme for sediments and sedimentary rocks (Nichols 2009).

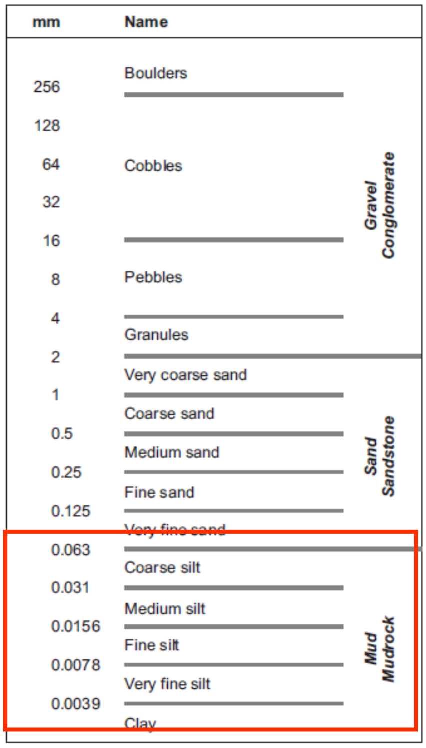


Figure 7: The Udden-Wentworth grain-size for clastic sediments (Nichols 2009).

3.1.1 Mineralogy

In terms of origin, most shale rock's constituent minerals are either allogenic or authigenic. Allogenic minerals are clasts of rocks and minerals brought into sedimentary basins, in which the shales are formed, from external sources, as detrital terrigenous material derived from rock weathering. Common allogenic constituents are quartz, feldspars, mica. Authigenic minerals are formed by sediment precipitation from water or alteration such as diagenetic processes: cementation and recrystallisation. Carbonates are the most common authigenic minerals.

Shale mostly composes of clay minerals. In practice, clay content in shales is higher than about 40 % (Fjær, Holt, et al. 2008).

Clay minerals comprise clay-sized particles and commonly form as breakdown products of feldspars and other silicate minerals. They are a group of phyllosilicate minerals with a layered crystal structure, and compositionally, they are aluminosilicates.

The crystal layers are made up of silica with aluminium and magnesium ions, with oxygen atoms linking the sheets. Tetrahedrons are constituents of the tetrahedral crystal layer and octahedrons are of the octahedral layer (Fig. 9a). Two layering patterns occur, one with two layers, the kandite group, and the other with three layers, the smectite group (Fig. 8). Figure 9b shows the structure of main clay minerals and the thickness of the tetrahedral-octahedral-tetrahedral (TOT) sequence of layers.

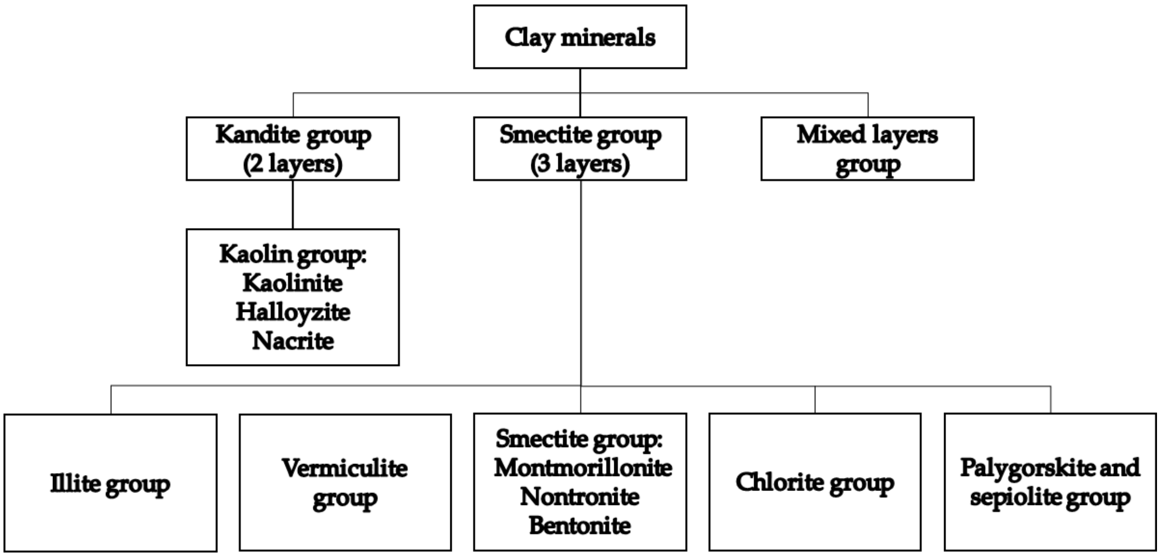


Figure 8: Clay minerals classification.

The kandite group includes the kaolin group. Kaolinite is the most common member of the kaolin group. It is generally formed in soil profiles in warm, humid environment where acidic waters intensely leach bedrock lithologies such as granite. The bond between the tetrahedral and octahedral layers is through the hydrogen bond. The bond is relatively strong, preventing hydration between the layers and allowing several layers to build up.

The three-layer clay mineral is illite, which is related to the illite group. It is the most common clay mineral in sediments formed by the decomposition of some micas and feldspars in temperate areas where leaching is limited. The space between the TOT sequence of layers is occupied by poorly hydrated potassium cations responsible for the absence of swelling.

Clay minerals of the smectite group include the expandable or swelling clays such as montmorillonite, which can absorb water within their structure. The bond between TOT sequences of layers is relatively weak, which results in water and exchangeable cations (K^+, Na^+, Mg^{2+}, Ca^{2+}, etc.) in interlayers. Montmorillonite is a product of more moderate temperature conditions in soils with neutral to alkaline pH. It also forms under alkaline conditions in arid climates.

Chlorite is a three-layer clay mineral that forms most commonly in soils with moderate leaching under fairly acidic groundwater conditions and in soils in arid climates. The TOT sequence of layers in chlorites are separated by an octahedral layer with two- or trivalent cations (Mg^{2+}, Al^{3+}, Fe^{2+}, Fe^{3+}). Chlorites are non-expandable and non-swelling clays.

Shales with abundant smectite and illite are susceptible to adsorb water into the formation (which eventually creates significant swelling) due to their larger surface area and cation exchange capacity (CEC) than other clay minerals, such as kaolinite and chlorite.

CEC impacts the reactivity of clay minerals, and most clay minerals with high CECs (>10 meq/100 g) form strong negative charges on the clay surface and therefore easily attract cations from the surroundings to maintain electrical neutrality. However, different clay minerals have different CECs, depending on their structural charges and cation substitution. For example, the CECs of smectite (80–150 meq/100 g), illite (10–40 meq/100 g), kaolinite (3–15 meq/100 g) and chlorite (10 meq/100 g) are quite different (Drever 1988).

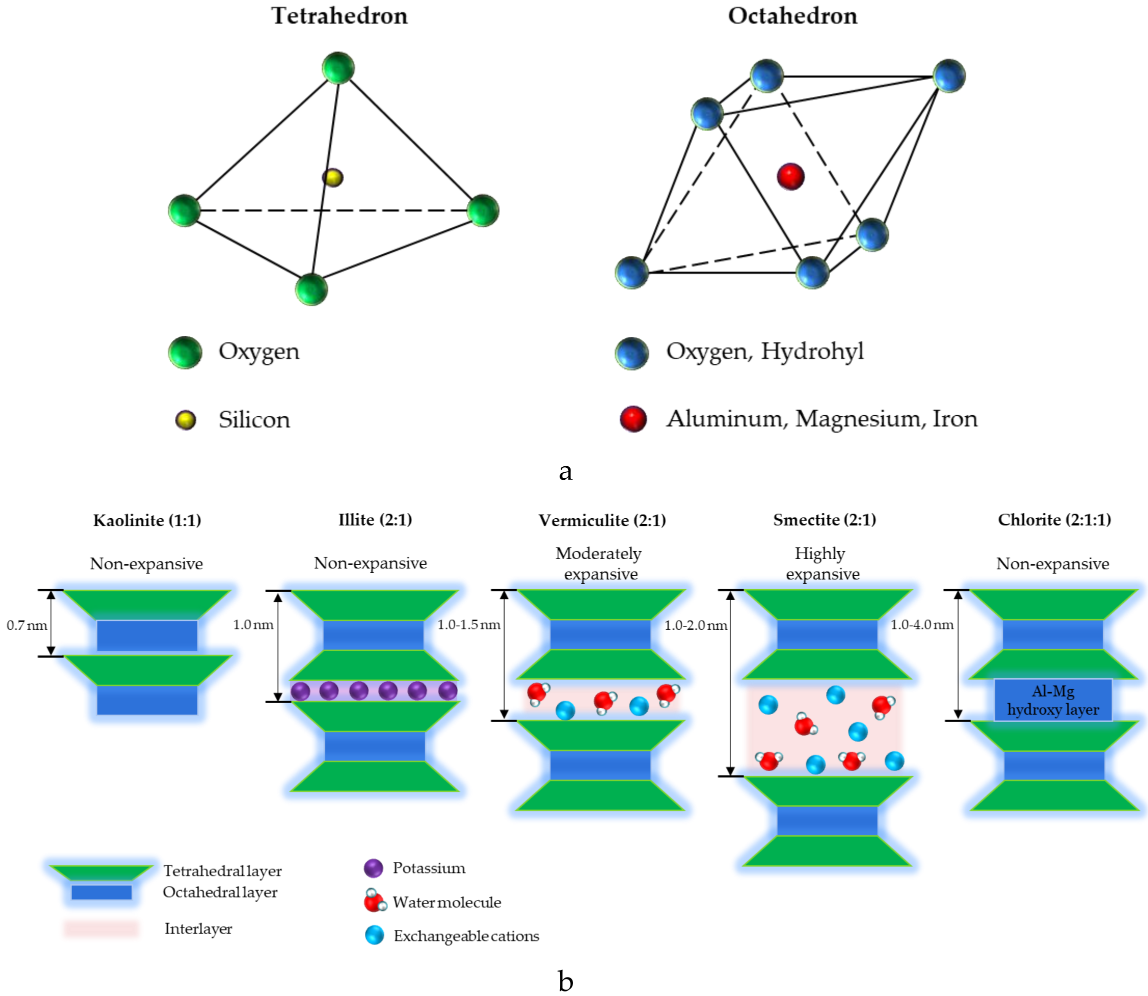


Figure 9: Clay minerals structure: a – tetrahedron and octahedron; b – structure of clay minerals group [adapted from (Grotzinger und Jordan 2014)].

The rock mineralogy is comprehensively studied on core plugs and drill cutting samples extracted from a small number of wells within a field. The visual description is conducted, and the conclusion regarding the rock type and lithology, colour, texture, grain size and shape can be done.

The following analyses are performed for more detailed compositional analysis:

- petrographic analysis of thin sections;
- grain size analysis (laser or sieve);
- scanning electron microscopy (SEM);
- X-ray diffractometry (XRD);
- X-ray fluoroscopy (XRF).

The core data is not available in all wells, so it is important to properly calibrate well logging data to core and cuttings data and elaborate the appropriate petrophysical model.

The main concern is core extraction from shale formation intervals, mostly the extraction is not performed at all, or the interval of extraction is not sufficient. The solution is running the neutron induced gamma ray spectroscopy logging tool, which can measure accurate mineralogy and TOC.

3.1.2 Total Organic Carbon (TOC)

TOC in the shale rock is defined as a content of organic matter (OM) expressed by the weight percentage of organic carbon. OM is primarily defined as organic compounds that are derived from cells or tissues of living organisms. In the case of shales, these are mostly phytoplankton organisms.

As it is shown in Figure 10, organic matter is a part of the rock matrix. The minimum TOC for shales is considered a 2 % wt TOC.

The investigations of how TOC affects the shale formation's displacement mechanisms towards the casing have not been conducted. However, clay swelling depends on the TOC content; that's why this parameter should be considered during the assessment of the shale formation. The study shows that sedimentary organic matter in soils is thought stabilizes soil aggregates by lowering the wettability, thus decreasing interaction with water (Chenu, Bissonnais and Arrouays 2000). TOC can be determined with carbon and sulphur analyzers in a laboratory.

3.1.3 Petrophysical Properties

The main petrophysical properties are porosity and permeability. To characterize the shale barrier, these parameters shall be identified.

Porosity

A typical shale rock volume is composed of a matrix from inorganic minerals and organic matter, along with pore space between these components (Fig. 10). Two types of porosity are distinguished: total porosity and effective porosity. The total porosity is defined as the fraction of void space within porous rock. Effective porosity is defined as the fraction of interconnected pores.

Pore sizes in shale are very small, typically between 5 and 25 nm. Usually, the total porosity is 19–20 %. In addition to relatively large amounts of the total porosity, shales may also contain significant effective porosity (8–12 %). The North Sea shales porosity is in the range of 30–55 % (Fjær, Holt, et al. 2008).

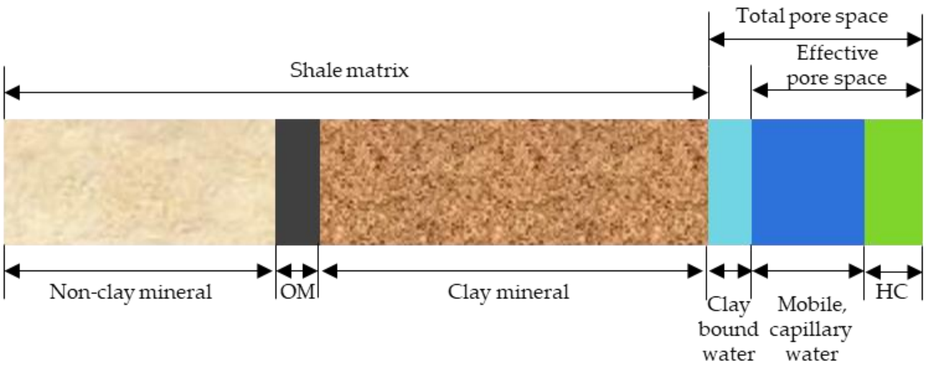


Figure 10: Schematic of the shale rock content [adapted from (Grotzinger und Jordan 2014)].

Permeability

Shale rock has low permeability that does not allow the flow of fluids easily. In most cases, hydraulic fracturing is necessary to connect micro- and nano .pores or pre-existent micro-fractures.

It is shown in Figure 11 that a pack of mixed cuttings from the Hordaland and Rogaland Groups at the Valhall field have been exposed to an increase in effective stress. The permeability of a pack of cuttings decreases with the increase of stress applied. Shale permeability normally has permeability values in the range of nanoDarcy, while a high-quality laboratory class G cement has10 to 20 µD (Kristiansen, Dyngeland, et al. 2018).

The North Sea shales permeability is in the range of 21 nD to 6.6 µD.

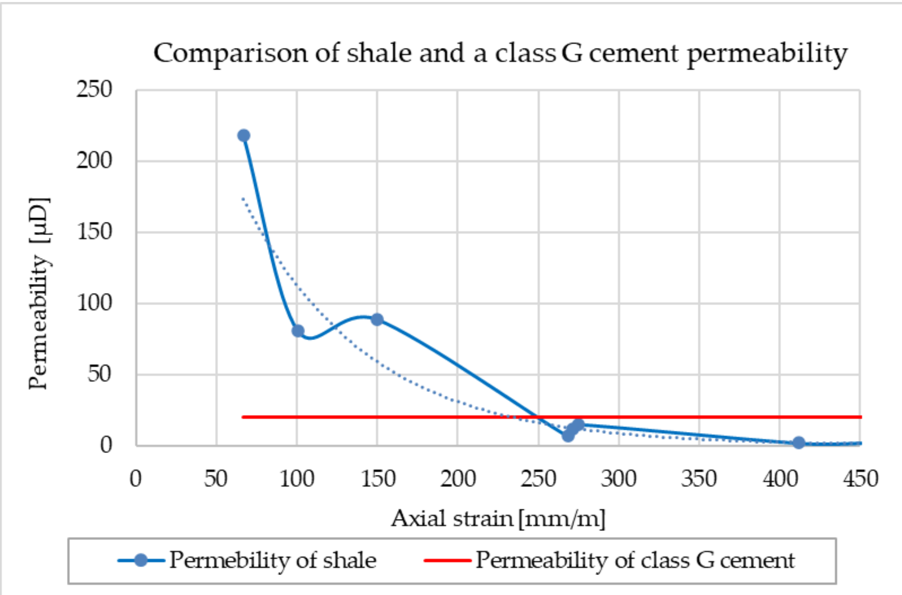


Figure 11: Comparison of shale permeability and cement class G permeability (Kristiansen, Dyngeland, et al. 2018).

Permeability is usually measured in porous materials using either water, nitrogen or air as the flowing medium. When qualifying barrier materials (Appendix B), it is considered to test materials in terms of nitrogen permeability since it is likely to be the escape of gas which is the key issue in the case of barrier materials.

For gas permeability measurement, a similar apparatus to the Hassler cell with air is used. To ensure nitrogen is not able to divert around the specimen, the sides are confined within a pressurized sleeve or triaxial cell.

3.1.4 Mechanical Properties

Shale texture is strongly anisotropic. This is often seen through a plane of weakness along which the shale easily splits. It implies that all non-scalar physical quantities will be anisotropic. This fact is often ignored in practical rock mechanical analysis due to a lack of data (Fjær, Holt, et al. 2008).

Based on a large data analysed, unconfined compressive strength (UCS) increases with decreasing porosity, and a relation of the form was proposed in Equation 1.

$$UCS = 193 \cdot \phi^{-1.14} \tag{1}$$

where UCS is the unconfined compressive strength given in [MPa], and φ is the total porosity given in [%] (Fjær, Holt, et al. 2008).

P. Horsrud (2001) studied North Sea shales and confirmed a proportionality between Young's modulus and unconfined strength approximately 150. The compressive strength is typically 10-15 times higher than the tensile strength.

From the extrapolation techniques bulk modulus varies between 5 and 25 GPa and shear modulus lays in the range of 4 and 10 GPa. These numbers depend on which type of clay mineral (kaolinite, illite, smectite) is prevailing, particularly on the adsorbed or bound water present within minerals and on mineral surfaces.

Also, P. Horsrud (2001) demonstrated that P-wave velocity measurements show a good correlation to shale strength. P-wave velocity can be derived from measurements on drill cuttings or from the log and seismic data. The relation is the following:

$$UCS = 0.77 \cdot \phi \cdot {V_p}^{2.93} \tag{2}$$

where Vp is the compressional velocity given in [km/s].

In Figure 12 it is shown the comparison of UCS for North Sea shales and UCS for the class G cement versus interval travel time. UCS of cement material is equal to 5250 psi (36.2 MPa). It is seen that shale rock is normally weaker than the class G cement if the transit travel time is 85 ms/ft or higher. At first glance, the cement may be a better barrier material due to the higher strength, but it has been found that low shale strength properties can be a long-term benefit for a barrier. The cement is commonly fractured as a result of temperature and pressure changes in the well, and due to the high strength properties the fractures will not tend to close over time, while the fractures in low strength shale will close over time (Kristiansen, Dyngeland, et al. 2018).

Due to its plate-like structure, uncompacted and soft clay will normally have a low friction angle. As compaction and consolidation occur and porosity and fluid content decrease, the shale will develop a higher friction angle. This will affect the permeability, elastic properties and strength parameters of the shale. P. Horsrud (2001) demonstrated in most tests that the friction angle with high porosity shale was significantly low in the range of 10°–20°.

Standards for measurements of mechanical properties are listed in Appendix B.

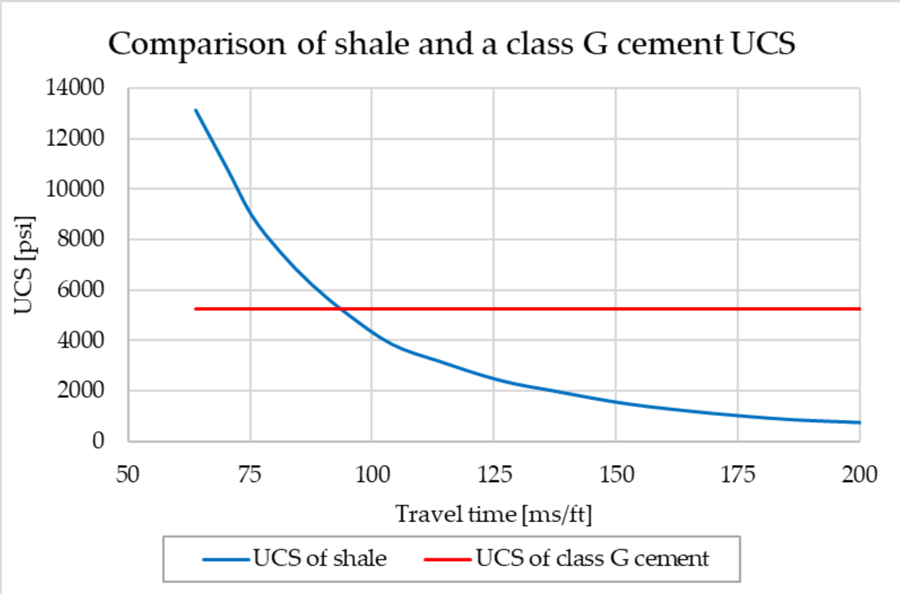


Figure 12: Comparison of shale UCS and UCS of cement class G (Kristiansen, Dyngeland, et al. 2018).

3.2 Shale Displacement Mechanisms

Theoretical studies and drilling observations have exposed that shale formation can be deformed and close the annular gap behind the casing (Enayatpour, et al. 2019). Formation displacement can be indicated as a decreased diameter of the wellbore called the ovalization process. This process may be observed during and after the well construction phase either slowly or rapidly.

There are various displacement mechanisms, which may occur in a combination or separately. There several main shale displacement mechanisms that are grouped into the following categories (Williams, et al. 2009):

- Rock failure;
- Compaction failure and consolidation;
- Liquefaction;
- Thermal expansion;
- Chemical effect/clay swelling;

- Creep.

3.2.1 Rock Failures

Tensile failure

Tensile failure occurs when the effective tensile stress across some plane in the rock exceeds the tensile strength. A rock having experienced tensile failure typically splits along one or few fracture planes (Fig. 13). Thus tensile failure is a highly localized inhomogeneous process. The fracture planes usually originate from pre-existing cracks, oriented nearly normal to the tensile stress direction (Fjær, Holt, et al. 2008).

Shear failure

Shear failure is the main failure mode when the rock is exposed to compressive stress. The failure occurs when the compressive stress exceeds the compressive strength.

It is typically seen that shale formations require mud weights higher than the pore pressure to remain stable with respect to shear failure calculations. The reduction of the mud density behind casing over time may be large when it comes to initiating this process (Kristiansen, Dyngeland, et al. 2018).

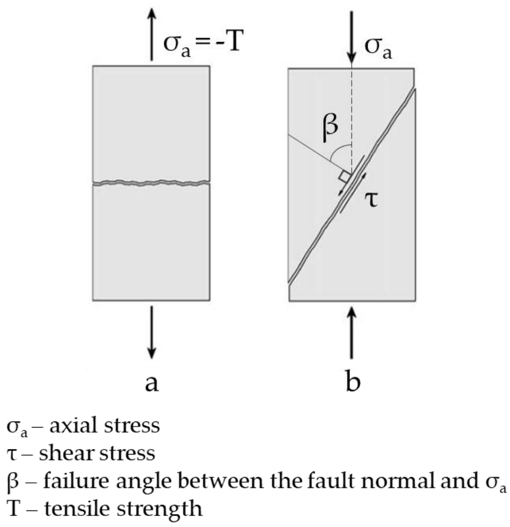


Figure 13: Rock failures: a – tensile failure; b – shear failure [adapted from (Fjær, Holt, et al. 2008)].

3.2.2 Compaction and Consolidation

A porous rock experiences a high hydrostatic pressure or pore pressure change, consequently, grains may loosen or break. The movement of grains into open spaces results in a closer packing regarded as reorientation. This process is known as compaction failure.

Consolidation is time dependent deformation induced by a change in the stress state due to pore pressure dissipation. Consolidation is described as the transient process, where pore pressure equilibrium is re-established after a change in the stress state (Fig. 14) (Fjær, Holt, et al. 2008).

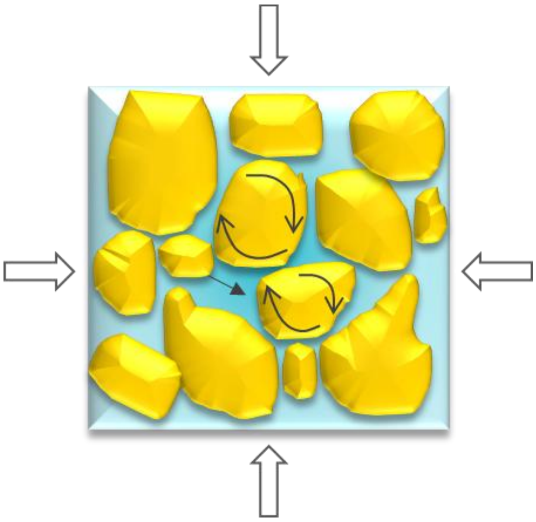


Figure 14: Consolidation process [adapted from (Fjær, Holt, et al. 2008)].

These processes are minor displacement mechanisms in the shale movement towards the casing (Kristiansen, Dyngeland, et al. 2018).

3.2.3 Liquefaction

A volume reduction and a corresponding reduction in the pore space causes of highly porous rock. If the rock fails under undrained conditions, the pore space reduction will lead to increased pore pressure. It leads to reduced effective stresses and reduction in confinement. For a poorly consolidated (or previously damaged) rock, this is a highly unstable condition that may result in severe deformations driven by the static shear stresses (Fjær, Holt, et al. 2008).

Soil liquefaction and related ground failure are commonly associated with large earthquakes. In common usage, liquefaction induced by rapid loading implies the loss of strength in saturated cohesionless soils due to pore pressure build-up during dynamic loading (Kristiansen, Dyngeland, et al. 2018). However, it is unlikely to form an annular barrier alone.

3.2.4 Thermal Expansion

In general, increasing the temperature eases rock movement and results in some degree of expansion. During the production life of wells, the temperature change is small, and besides, formation movement has been observed in shallow depths where temperatures are not high.

Mechanical stress caused by any change in temperature of a material is called thermal stress. The thermal axial strain and stress are described by Equations 3 and 4.

$$\varepsilon_a = -\alpha_T \cdot (T_1 - T_0) \tag{3}$$

$$\sigma_a = -E \cdot \varepsilon_a = E \cdot \alpha_T \cdot (T_1 - T_0) \tag{4}$$

where ε_a is the axial thermal strain in [mm/mm], σ_a is the thermal stress in [MPa], E is Young's modulus in [MPa], α_T is the coefficient of linear thermal expansion in [°C^{-1}], and T_1-T_0 is a temperature change in [°C] (Fjær, Holt, et al. 2008).

As seen in Figure 15, for a 12 $^1/_4$´´ borehole diameter with a 9 $^5/_8$´´ casing diameter, even with a high temperature difference, the thermal effects only contribute to about 3 % of the required displacement in the North Sea shales. Therefore, thermal expansion is a minor displacement mechanism (Skjerve 2013).

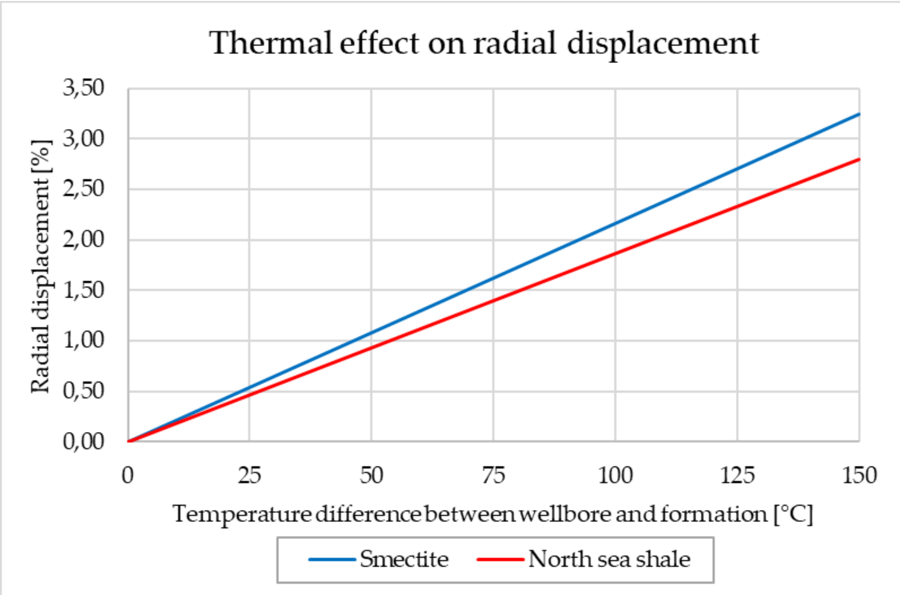


Figure 15: Thermal effects on required radial displacement in a 12 $^1/_4$´´ borehole diameter with a 9 $^5/_8$´´ casing diameter for smectite clay and North Sea weak shale (Skjerve 2013).

3.2.5 Clay Swelling

Osmosis is one of time-dependent chemical effects that promotes chemical interaction between the drilling fluid and the formation. The basis for osmosis is the presence of a semi-permeable membrane that permits water molecules to pass but prevents ions from entering the shale. The semi-permeable membrane is oil-based mud (OBM) or shale itself in contact with water-based mud (WBM).

However, it is well known that the ionic exchange occurs between shale formation and drilling fluid because the osmotic membrane is leaky, which is handled by introducing a membrane efficiency $\sigma < 1$. The osmotic potential $\Delta\Pi$ expressed in [J/l] is calculated by Equation 5.

$$\Delta\Pi = \sigma \cdot \frac{R \cdot T_{abs}}{V_w} \ln \frac{a_{w,df}}{a_{w,sh}} \tag{5}$$

where σ is the membrane efficiency, R is the molar gas constant [8.31 J/mol·K], V_w is the molar volume of water [0.018 l/mol], T_{abs} is the absolute temperature in [K], $a_{w,df}$ is the chemical activity of water in the drilling fluid, and $a_{w,sh}$ is the chemical activity of pore water in the shale. The activity denotes the effective concentration of water in a solution, so that $a_w = 1$ for fresh water, while $a_w < 1$ for salt water (Fjær, Holt, et al. 2008).

The ionic exchange tends to alter shale properties. In particular, exposure of smectite-rich shale to *KCl* mud causes significant osmotic swelling due to exchanging potassium and sodium ions. It leads to a plasticity increase and is beneficial for borehole stability. However, it does not contribute to the shale displacement process as a creep mechanism.

Clay swelling relies on several factors such as temperature, water, salinity, and TOC. It should be considered when selecting the type of drilling fluid and planning the well P&A using the shale barrier.

3.2.6 Creep

Creep is a time-dependent deformation that may generate in materials under constant stress. Creep originates from visco-elastic effects in the solid framework and occurs in both dry and saturated rocks.

There are known three stages of creep following a change in the stress state shown in Figure 16. The first stage is called transient (or primary) creep, where the rate of the time-dependent deformation decreases with time. The process may be associated with a minor spreading of 'stable' microfractures. If the applied stress is reduced to zero during the primary creep stage, the deformation will ultimately decrease to zero.

In the next stage, the deformation rate is constant. This is called steady-state (or secondary) creep. If the applied stress is reduced to zero during this stage, the deformation will not vanish completely. Steady-state creep thus implies a permanent deformation of the material.

Eventually, the deformation rate may increase with time. This is called accelerating (or tertiary) creep. This stage leads rapidly to failure. The process may be pertained to rapidly spreading of 'unstable' fractures (Fjær, Holt, et al. 2008).

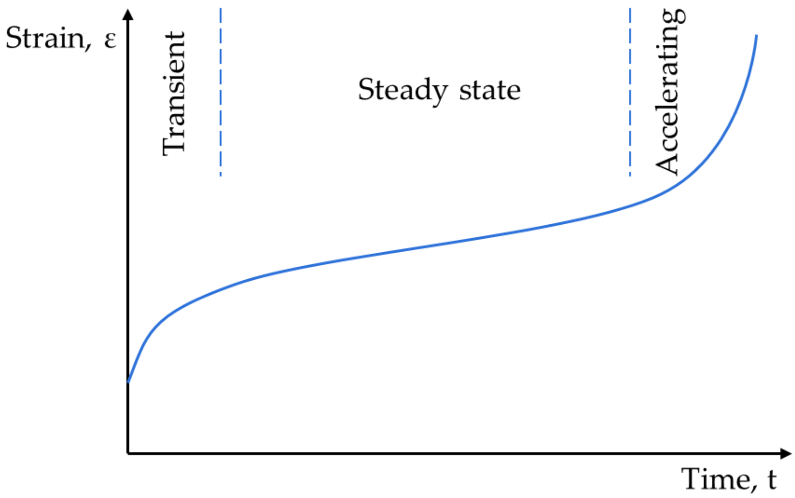


Figure 16: Strain versus time for a creeping material (Fjær, Holt, et al. 2008).

As shown in Figure 17, the creep performance at constant temperature is dependent on the magnitude of the applied stress. For low and moderate stresses, the material may practically stabilize after a period of transient creep. For high stresses, the material may rapidly go through all three stages of creep and fail at the end.

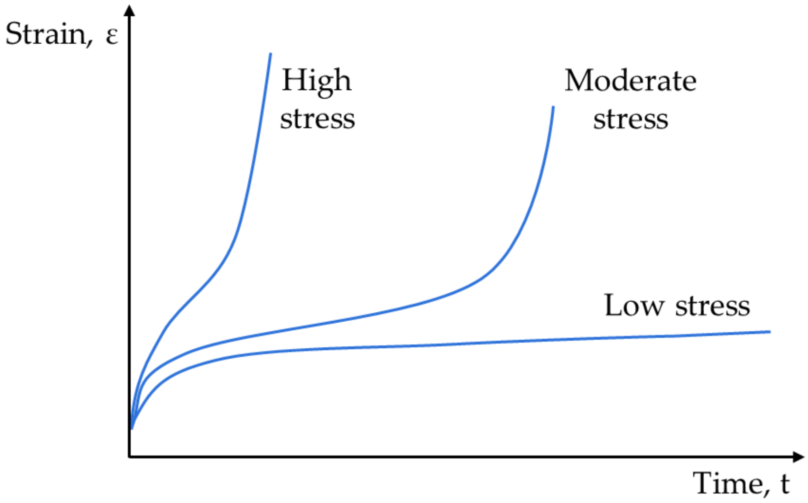


Figure 17: The development of creep depending on the applied stresses (Fjær, Holt, et al. 2008).

The elevated temperatures at constant stress result in increased creep deformation rates, increased instantaneous strain, reduced rock strength and decreased rupture time, as shown in Figure 18. Heating low permeability shale formation leads to increased pore pressure due to the thermal expansion of pore fluid greater than the thermal expansion of the rock matrix. It may lead to a decrease of effective stress that can produce plastic shear deformation.

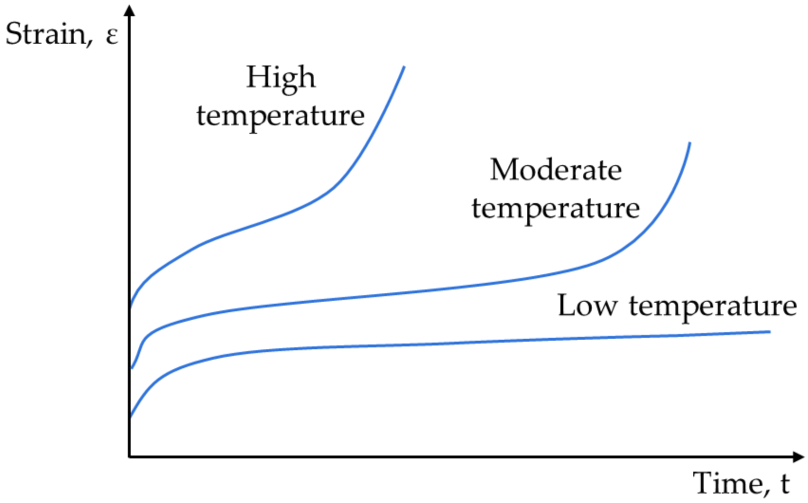


Figure 18: The development of creep for different temperature values (Fjær, Holt, et al. 2008).

The time scale of a creep varies over a wide range. It can last for minutes or years. Thus, forming and activating shale barriers is a time-consuming process.

It is generally presumed that hydrostatic stresses alone will not produce creep effects and creep is proportional to the deviatoric stresses. Thus creep virtually decreases the shear modulus and Young's modulus of a material, Poisson's ratio grows, while the bulk modulus remains constant (Fjær, Holt, et al. 2008).

Out of the above mentioned mechanisms it is thought that creep emerges to be the major displacement mechanism, more likely in combination with shear failure and clay swelling, and makes up to 90 % to the shale displacement.

In order to understand the self-sealing process, the creep test 'Shale Barrier test' has been developed and described in the article of Fjær, et al. (2018). This test aims to investigate the capability of a specific shale material to form a sealing barrier around a casing under a given set of conditions respectively to stress, pore pressure, temperature, and fluid exposure.

The shale barrier test is performed on a hollow cylinder specimen (OD: 100 mm, ID: 10 mm, length: 100 mm) under isotropic external stress and with separate pressure control of the borehole and pore pressures (Fig. 19). Pressure control is achieved using two-piston continuous-flow metering pumps. Thus the fluid volumes are measured and the borehole, and pore pressure volumes are used in permeability calculations. External sample strains are measured axially and radially (Fjær, Stenebråten and Bakheim 2018).

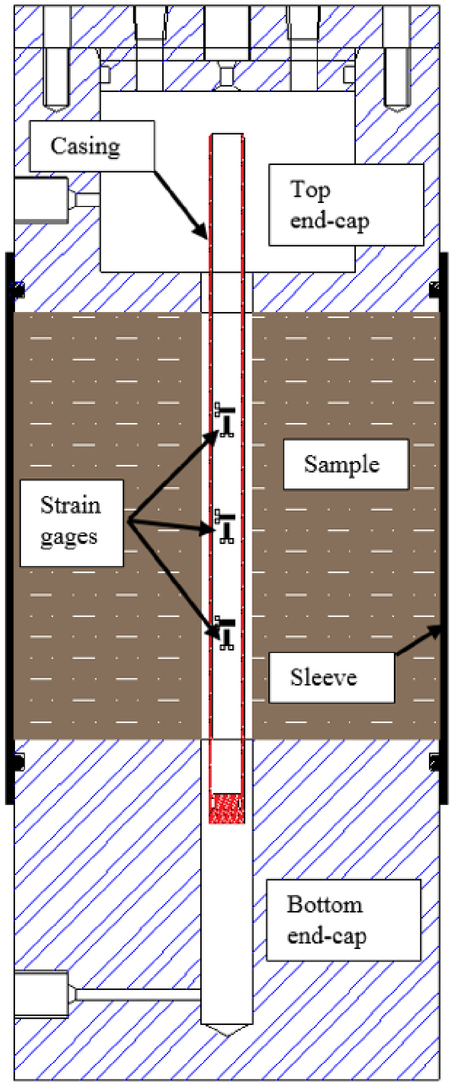


Figure 19: Test equipment (Fjær, Stenebråten and Bakheim, Laboratory Test for Studies on Shale Barrier Formation 2018)

3.2.7 Creep Parameter

Acoustic open-hole log data refers as input to borehole stability analysis during the well construction phase by estimating shale strength through empirical correlations (e.g. Horsrud, 2001), and further has a potential for selection of formations that are likely to form barriers around the casing.

In the work of Kristiansen, et al. (2018), the relationship between the creep rate and Young’s modulus was studied on shale core plugs from the Sele formation in the Rogaland Group at the Valhall field. The relation of Young’s modulus and the P-wave velocity was mentioned earlier in Equation 2. Consequently, the relationship of the creep rate and the interval travel time can be established.

The creep parameter is defined as in Equation 6.

$$C = \frac{\varepsilon_{vol} - const}{\log t} \tag{6}$$

where C is the creep parameter given as [%] per log cycle of time, ε_{vol} is the volumetric strain in [%], and t is time in [hour].

The relationships between volumetric, shear creep parameters and interval travel time for the Valhall test data are shown in Figure 20. It is also seen the temperature dependence of the creep parameter. As the temperature rises, the creep rate will increase.

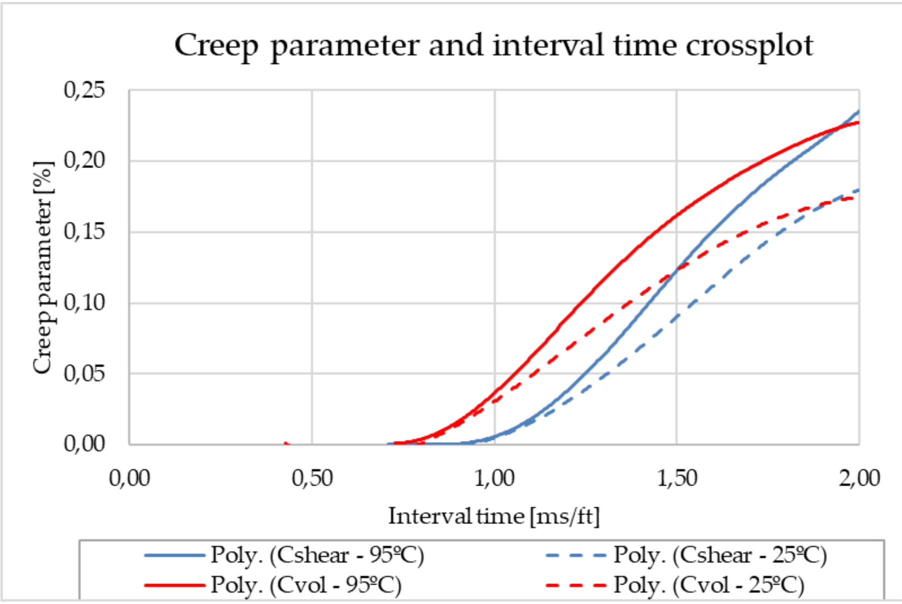


Figure 20: Trend lines of shear and volumetric strain creep rate parameters versus DTC for 25°C and 95°C based on the data for Sele at Valhall (Kristiansen, Dyngeland, et al. 2018).

The creep parameter was calculated from the acoustic open-hole log data using the obtained relationship shown in Figure 21. The calculated creep parameter allows predicting which shale formation might be a potential barrier. The potential barriers are Lark and Horda shale formations in this particular case, as they have the high creep parameter. However, note that a more advanced predictor must probably consider more parameters than only interval travel time.

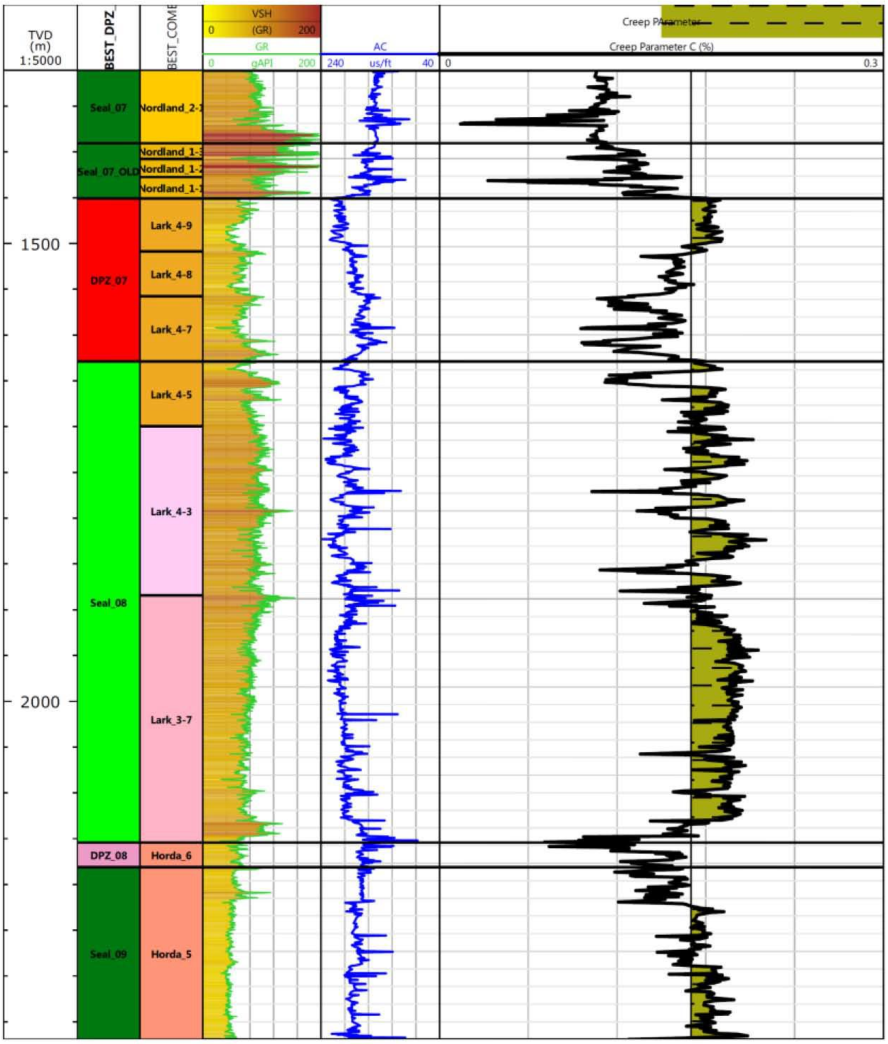


Figure 21: Prediction of the creep parameter from acoustic open-hole log data from the Valhall field (Kristiansen, Dyngeland, et al. 2018).

3.3 Publications related to SAAB

The ductile and creeping formations are of great interest to drilling engineers. The lateral movement of salt and shale formations towards the well casing could jeopardize the well integrity by causing the tubular element to fail what is known as casing collapse. Loading of salt and shale on the well casing has been comprehensively studied (Willson, Fossum und Fredrich 2003). Normally the lateral movement is considered undesirable. However, the advantage of the mechanism can be taken to create an annular barrier behind casing.

The concept of SAAB in P&A operations has been studied since 2006. At the Oseberg oil and gas field in Norway, it was occasionally observed that intervals above predicted top cement had a log response similar to the response of good cement bonding during bond logging operations (CBL, USIT) in the casing. Later annular barrier was pressure tested, and no leakage in the interval was detected. Hydro & Statoil declared that the shale formation had successfully been used to resolve critical barrier issues or as a cheaper and safer way to establish barriers in more than 100 wells. Average cost reduction of P&A operations is estimated to 15 MM NOK (Carlsen 2012).

The article of Williams, et al. (2009) summarizes results of logging and pressure testing carried out in a number of wells of North Sea fields. Essentially, CBLs in combination with VDLs and ultrasonic azimuthal bond logs response were calibrated to pressure testing result in one well. In subsequent wells, pressure testing was not required since the calibrated log response was used to detect shale annular barriers. This research has proved that the presence of shale annular barriers can be verified by using wireline logs only (Williams, et al. 2009).

According to Williams, et al. (2009), shales qualified as annular barriers belong to the argillaceous Tertiary and Cretaceous sequences:

- Tertiary 'Green Clay' sequence of the Hordaland Group;
- Cretaceous 'Nise Clay' sequence of the Shetland Group.

The idea to qualify the formed shale barrier using acoustic and ultrasonic logging techniques without the need to verify it by pressure testing explicitly was also studied by Lavery, et al. (2019). A comprehensive road map is described to identify shale annular barriers. It was tested in wells of the Jotun field, located on the Utsira High approximately 200 km west of Stavanger, Norway (Lavery, Jambunathan und Shafikova 2019).

The results of ultrasonic measurements on shales in the laboratory and ultrasonic properties of creeping formations are summarized by Holt, et al. (2017). Experiments were conducted on specimens of Tertiary Oligocene shale and Upper-Jurassic shale. These results help describe the driving displacement mechanisms and distinguish between barrier-forming and non-barrier forming shales (Holt, Fjær and Larsen 2017).

Several studies are dedicated to ultrasonic logging modifications and the advanced bond-log analysis technique. Examples are reported in publications: (Sirevaag, Johansen, et al. (2018, 2020) and Bauer, et al. (2021).

In 2013 the concept of the formation sealing barrier was revealed within the master thesis project "Evaluation of Shale Formations as Barrier Element for Permanent Plug and Abandonment of Wells" at the Norwegian University of Science and Technology (NTNU) by Kristian Moum Skjerve. This thesis has revealed that as a possible solution, shales can be used in combination with viscoplastic or weight materials, particularly micro-barite, where the closing process of the whole annular gap would require too much deformation from the formation (Skjerve 2013).

An independent research organization SINTEF was implementing a project "Shale as a Permanent Barrier after Well Abandonment" with the lead of Erling Fjær in 2015-2018. SINTEF has specially designed a Shale Barrier Test, a downscaled simulation of the gap closure process enabling monitoring of sealing capacity and stress on the casing. Pre- and post-test CT (Computer Tomography) scans reveal the extent and nature of the formation barrier. Laboratory experiments and numerical modelling of the annular closure are described in the following papers: Fjær, Folstad and Li (2016); Bauer, et al. (2017); Fjær, Stenebråten and Bakheim (2018); Xie, Fjær and Detournay (2019).

Recent laboratory tests at SINTEF within the joint industry project "Logging Shale Barrier before Well Abandonment", which lasted from 2016 till 2019, provided an excellent opportunity to test the validity of the numerical inversion method. SINTEF developed a scaled-down combined 'pulse-echo' and 'pitch-catch' bond-log tool to be applied inside a metal tube inserted in a hollow-cylinder shale sample.

The thermal stimulation of shale barriers was comprehensively reviewed using the finite element analysis by Bauer, et al. (2017) and Thorbjørnsen (2017).

The empirical and numerical models of the creeping process were fully discussed in the master thesis "Formation as Barrier for Plug and Abandonment of Wells" by Katrine Fredagsvik (2017).

As a part of SINTEF project, the research of Kristiansen, et al. (2018) discussed how a shale barrier could be activated to form around the wellbore in shales with different properties. This can be carried out by inducing a pressure drop in the open annulus, heating the shale by a couple of 100 ºC, or chemical processes. The paper included verification from logs and pressure tests of the shale barriers from two wells at the Valhall field, where the pressure drop was implemented. The verified shale formation was, as predicted, Horda 1 formation, which is a part of the Hordaland Group.

In addition, the paper reviews the physical properties of shales, relevant deformation processes for shales forming a barrier. It was also described how these processes have been studied in the laboratory and modelled numerically. A comparison between the properties of cement and shale is also discussed in terms of how those will act as a well barrier material over a long time (Kristiansen, Dyngeland, et al. 2018).

The work was continued, and the technique of inducing a pressure drop in the open annulus has been accomplished in new wells at Valhall and a second field, Ula. Shale barriers have been verified with pressure tests and bond logs at Ula and Valhall in the Lark, Horda, and Lista formations in the Hordaland and Rogaland shales. Based on the observation of bond logs, the deeper shales in Cretaceous Åsgard and Mandal formations (the Cromer Knoll Group) at Ula also show strong potential to form shale barriers. These formations need to be verified with pressure testing in the future (Kristiansen, Delabroy, et al. 2021).

To qualify the barrier, time-lapse bond logging has been carried out in a number of wells Ula and results are demonstrated in the article of Kristiansen, et al. (2021). It allowed identifying the duration of forming a barrier. In some cases, the barrier formed instantly. However, mostly it takes weeks or months to create a required length of the shale barrier. Also, the strategy and the decision tree for the SAAB implementation were described within this P&A campaign.

The immense work on investigating and comparing different creep accelerating mechanisms was done by Enayatpour, et al. (2019) and Eric van Oort, et al. (2020). Five field core samples from the Lark-Horda shale formation were selected to conduct customized experiments that simulated the 'in-situ' conditions to fill in an annular space behind a casing string (Enayatpour, et al. 2019), (van Oort, et al. 2020).

Besides the North Sea shales, the Pierre shales have been tested for creep. The Pierre shale is a geologic formation in the Upper Cretaceous, which is encountered in the east of the Rocky Mountains in the Great Plains, from Pembina Valley in Canada to New Mexico. The laboratory experiments were conducted at a SINTEF laboratory as a part of the master thesis project at NTNU (Austbø 2016). More information about laboratory experiments and tests on the Pierre shale samples can be found in the following works: Holt, et al. (2019); Lavery, Jambunathan und Shafikova (2019)and Gawel, et al. (2021).

3.4 Qualified Shale Formations in the North Sea

The naturally creeping shale formations have been found from the southern North Sea and to the northern part of the Norwegian Sea, as shown in Figure 22. For example, a creeping formation has been met in Statfjord A and Grane fields; some degree of formation creep has been observed in all fields of the North Sea and the Norwegian Sea. However, no naturally creeping formation has been reported in the Barents Sea (Fredagsvik 2017), (Khalifeh M., Saasen A. 2020).

Figure 22: Overview of creeping and non-creeping formations in the North Sea, the Norwegian Sea and the Barents Sea: A – creeping formation area; B – non-creeping formation area (Fredagsvik 2017).

Shale formations that have already been qualified in the North Sea region are listed in Table 2 representing stratigraphic column with main geological ages. It is seen that shale formations mostly belong to Tertiary, Cretaceous and Upper-Jurassic geological periods.

These shale formation groups are dislocated in the NCS of the North Sea, and in other continental shelf sectors, these groups may be named differently. However, the zone of interest of all countries producing hydrocarbons in the North Sea region is the Tertiary Middle North Sea Group.

Qualification is the process to demonstrate the ability to fulfil specified requirements. Shale formations from each of these groups have been qualified either employing inferred measurements (logging) or direct measurements (pressure tests, lab experiments). Some formations are only studied to some extent and require further research.

The most explored shale formations are Lark and Horda that belong to the Hordaland Group in the NCS of the North Sea. They have been verified with bond logging, pressure testing and lab testing on core samples. A creep test has been performed with a core sample from well preserved Lark shale formation subject to its native state. Correlations between ultrasonic properties (velocity, impedance) and petrophysical properties obtained from this lab experiment promise to identify shale barriers from logs. Since rock velocities are largely unchanged after failure, open hole log data may be used to predict possible shale barriers (Holt, Fjær and Larsen 2017).

Hence, the physical properties of the Hordaland Group are described in Appendix C and taken as a reference.

<table>
<tr><th colspan="2">Period</th><th>Epoch</th><th>Group</th><th>Formation</th><th>Qualification method</th></tr>
<tr><td rowspan="9">Tertiary</td><td rowspan="3">Neogene</td><td>Pliocene</td><td rowspan="2">Nordland</td><td rowspan="2">-</td><td>pressure testing</td></tr>
<tr><td rowspan="2">Miocene</td><td>tested in laboratory</td></tr>
<tr><td rowspan="3">Hordaland</td><td rowspan="2">Lark</td><td rowspan="2">tested in laboratory; bond logging and pressure testing</td></tr>
<tr><td rowspan="6">Paleogene</td><td>Oligocene</td></tr>
<tr><td rowspan="2">Eocene</td><td>Horda</td><td>bond logging and pressure testing</td></tr>
<tr><td rowspan="5">Rogaland</td><td>Balder</td><td rowspan="2">bond logging</td></tr>
<tr><td rowspan="3">Paleocene</td><td>Sele</td></tr>
<tr><td>Lista</td><td>bond logging and pressure testing</td></tr>
<tr><td>Våle</td><td rowspan="2">bond logging</td></tr>
<tr><td colspan="2" rowspan="8">Cretaceous</td><td rowspan="6">Upper</td><td>Vidar</td></tr>
<tr><td rowspan="5">Shetland</td><td>Ekofisk</td><td rowspan="5">bond logging</td></tr>
<tr><td>Tor</td></tr>
<tr><td>Hod</td></tr>
<tr><td>Blodøks</td></tr>
<tr><td>Hidra</td></tr>
<tr><td rowspan="2">Lower</td><td rowspan="2">Knoll
Cromer</td><td>Åsgard</td><td rowspan="2">bond logging</td></tr>
<tr><td>Mandal</td></tr>
<tr><td colspan="2">Jurassic</td><td>Upper</td><td>-</td><td>-</td><td>tested in laboratory</td></tr>
</table>

Table 2: Qualified shale formations in the North Sea region.

3.4 Summary

A minimum set of physical shale characteristics was extracted by analyzing the tested formations that have exhibited the potential for creeping in and acting as a barrier. The following characters do not qualify any shale as a barrier, however, they are an indication of a high chance that SAAB could be further qualified through field measurements and lab testing.

The shale rock to be qualified as a barrier should have the following characterisation:

- high clay content more than 40 % of a total mineral content with an abundant content of smectite;

- low content of cementing minerals: quartz less than 25 % and carbonates (calcite and dolomite) less than 5 %;
- low permeability less than 20 μD;
- high porosity;
- low acoustic velocity;
- low values of geomechanical parameters: cohesion, UCS and internal friction angle.

Most shales exhibit a certain degree of plastic behaviour. Additionally, shales with a low content of cementing minerals are likely to have a lower threshold for plastic flow and a higher ability to withstand large plastic deformation without breaking up. Shales will likely be better candidates for the annular barrier.

It is substantially to study the shale rock by inspecting cutting and core samples and conducting lab tests on them. If shale rock meets the criteria listed above, it might potentially form a seal around the casing. So, further studies of shale formation, such as logging and pressure testing, can be carried out. However, to meet all criteria may not be directly necessary as good bonding has also been observed between casing and formation with low smectite content (Carlsen 2012).

Chapter 4 Technologies for Inferred and Direct Measurements of Annular Seal

This chapter will discuss a verification process of a formation annular seal using cased hole logging and pressure testing. Inferred measurement is an approach to measuring things indirectly or calculating the unknown parameter from known parameters through their relation, e.g. the bond between cement and casing is estimated indirectly by measuring acoustic log response. Direct measurement is when a required parameter can be explicitly measured, for instance, the pressure that formation can withstand.

According to all existent standards and requirements mentioned in Chapter 2, the presence of a formation seal shall be verified with at least two independent logging measurements and pressure testing. Pressure testing is enough to conduct in a limited number of wells for the specific formation within the field, and direct physical tests jeopardize the well integrity as it requires perforation of the casing. So, if pressure testing and logging results are sufficient, only bond logging will be carried out in wells for the same formation with the geological similarities. Differential pressure testing is required if the log response is not conclusive or uncertain geological similarity.

Moreover, petrophysicists need to be provided with information about the physical, acoustic and mechanical properties of fluids, tubular, cement and formation to perform a correct interpretation of logging data. Before conducting cement evaluation logging (CEL) the following input data should be provided:

- Well design: number of casing strings, casing diameter and thickness, the length of each section, casing shoe depths, and type of steel.
- Information about the fluid filling the wellbore: type of fluid, density, acoustic properties.
- Information about cementing operations: top of cement, cement density and acoustic properties, results of processing and interpretation of the previous cement evaluation.
- Stratigraphic column: top and bottom depths of shale formations.
- Mineral composition of shales and their petrophysical, geomechanical and acoustic properties.

The approximate values can be assumed in old wells where this data may not be obtained since annulus fluid is altered and cement sheath might be degraded.

4.1 Well Logging Tools

Sonic and ultrasonic logging tools are used to assess the casing and cement quality and provide information about the Top of Cement (TOC) and the depth interval of a good bond between the casing and environment behind the casing. Such measurements can be conducted wither after wellbore cementing works during the well construction phase, or the intervention phase, or the abandonment phase.

The following information shall be provided before a commitment to P&A operations:

- the length of annular cement coverage and TOC;
- the presence and the length of formation barriers that have been formed around the casing;
- the quality of the bond between the casing and the surrounding environment (cement or formation).

Subsequently, based on this data and analysis of the zonal isolation, the decision regarding the P&A method is taken.

4.1.1 Sonic Logging Tool

CBLs and VDLs are acquired using a sonic logging tool and the operating principle of this tool is explained below.

The standard CBL tool consists of a transmitter that produces a low frequency omni-directional acoustic pulse in the range of 10-20 kHz (Fig. 23). The pulse initiates a longitudinal vibration of the casing. It propagates through the borehole fluid, casing, cement or/and formation before being detected at the receivers conventionally placed at 3 ft (0.9 m) and 5 ft (1.5 m) spacing from the transmitter (Williams, et al. 2009).

The data recorded represents averaged values over the casing circumference. It compromises the amplitude of the first positive peak E_1 of the sonic waveform received at 3 ft and the full waveform received at 5 ft, as shown in Figure 23. When bonded to a stiff and solid material, the vibration of the casing is attenuated, and the E_1 amplitude is small. In a free pipe, the casing arrivals are strong, and the E_1 amplitude is high (Williams, et al. 2009).

The CBL tool measures signal amplitude and attenuation displayed on the log in millivolts (mV) or decibel (dB). The transit time is called the time taken by the wave to travel from transmitter to receiver; it is defined automatically.

The VDL provides visualization of the entire waveform at the 5 ft receiver. In a free pipe, the casing arrivals are strong and appear parallel on the log, and few formation arrivals are observed. In a perfectly cement bonded wellbore, weak casing arrivals followed by strong formation arrivals are observed.

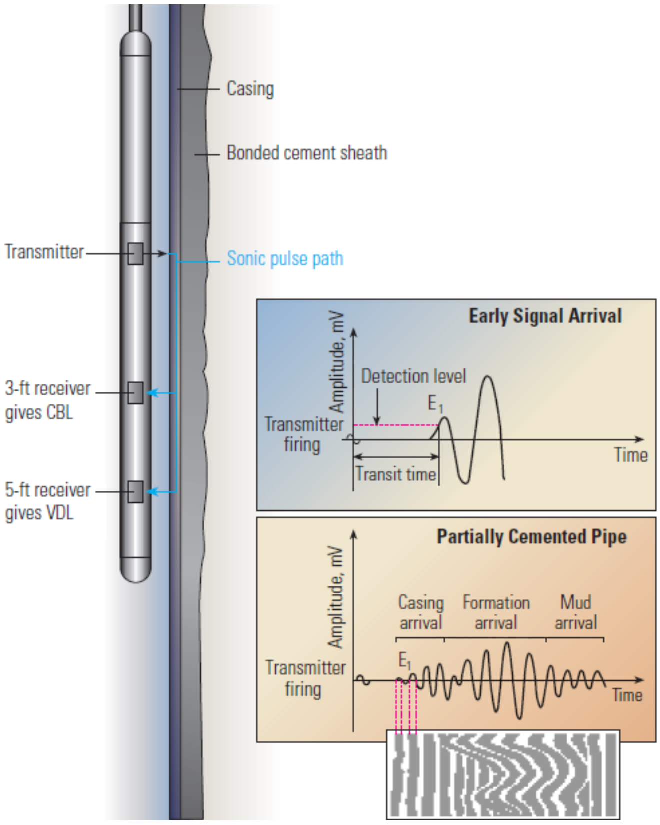


Figure 23: Sonic logging tool (Bellabarba, et al. 2008).

However, it should be noted that before logs being interpreted, corrections shall be applied. Wellbore conditions affect the attenuation of sonic signals, and measurements are dependent on the following parameters:

- casing thickness;
- mud weight;
- fluid type;
- cement type;
- wellbore geometry configurations;
- tool eccentricity.

To minimize these effects when interpreting the CBL data, a calibration in a free pipe section is required to compensate for wellbore differences, considering that wellbore conditions do not change over the entire well. Later, this can be estimated with the transit time value, which varies with casing inner diameter and mud properties (Williams, et al. 2009). Fluid compensation factor, cement type compensation factor, CBL adjustment factor for the calibration the ´free pipe´ amplitude to the theoretical value are applied to correct the raw CBL data.

The primary drawback of the conventional sonic CBL-VDL tool is that it does not register data azimuthally to differentiate channels, contaminated cement, microcannuli over the casing circumference and tool eccentricity. However, it is mentioned in the article of Lavery, et al. (2019) that the advanced CBL provides azimuthal information about the material behind the casing. The 3 ft receiver is divided into eight sectors to provide radial amplitude readings.

4.1.2 Cased Hole Ultrasonic Imaging Tool

Compared to the CBL tool, the ultrasonic tool scans the casing at 7.5 revolutions per second with an azimuthal resolution of 5 or 10 degrees providing 36 or 72 separate waveforms at each depth (Fig. 24). An ultrasonic tool’s transducer emits an ultrasonic wave perpendicular to the casing with a high frequency between 250 and 700 kHz to excite the casing into its thickness resonance mode (Williams, et al. 2009).

Measurements are processed to yield the casing thickness, internal radius and inner wall smoothness from the initial echo. The peak amplitude of the first reflection is used to form a textural image of the internal casing wall. The internal casing radius is determined from the first arrival travel time. If to select the appropriate transducer frequency, the casing thickness can be determined as half the wavelength at the casing resonance frequency (Lavery, Jambunathan und Shafikova 2019).

The radial image of the material's acoustic impedance behind the casing can be acquired from the resonance decay. A good bond causes immediate resonance decay, while free pipe rings and produces echoes.

When the signal emitted by the rotating transducer reaches an interface between the casing and the cement/formation, a portion of the signal is reflected at the interface. In contrast, some of the signals are transmitted across the interface. The portion of the reflected and transmitted energy relies on the acoustic impedance contrasts of the material at the interface (Lavery, Jambunathan und Shafikova 2019). The accuracy of the acoustic impedance measured depends on the accuracy of the mud impedance that is known. The mud impedance is estimated before logging is conducted.

The cement acoustic impedance is then defined as gas, liquid or cement based on the thresholds set for acoustic impedance boundaries between these materials (Fig. 27). The acoustic impedance is then classified as gas when it is normally less than 0.3 MRayl, liquid when between 0.3 MRayl and 2.6 MRayl, or solid material when it is larger than 2.6 MRayl (Williams, et al. 2009).

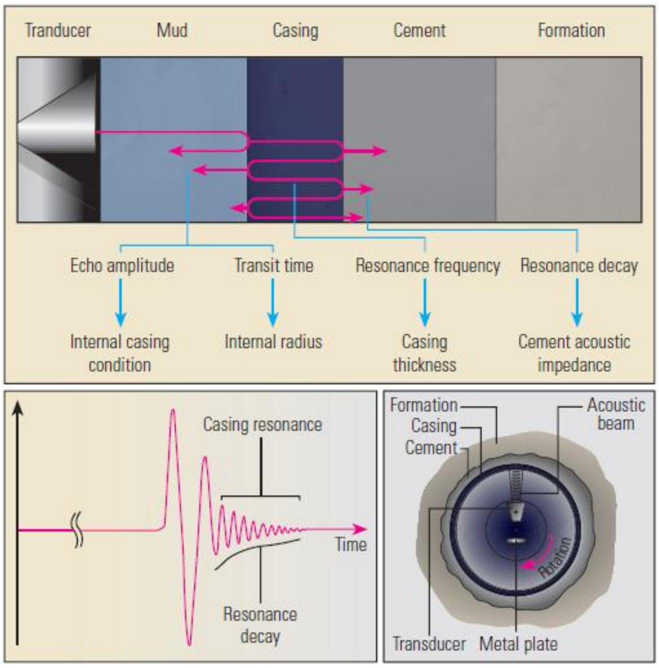


Figure 24: Cased-hole ultrasonic tool basics (Bellabarba, et al. 2008).

Nevertheless, ultrasonic tools based on the 'pulse' principle have drawbacks, and due to this fact, the application of USIT can be limited. Logging in highly attenuative mud impacts the measurements due to the low signal-to-noise ratio.

The signal weakens rapidly because of the high acoustic impedance contrast between the steel and the surrounding material (mud inside the casing and cement or formation behind the casing). Echoes occurring from acoustic contrasts outside of the casing are typically undetectable unless they are tight to the casing and strongly reflective surfaces (Bellabarba, et al. 2008).

In case of low impedance of the material behind the casing, the ´pulse-echo´ technique has difficulty distinguishing without ambiguity whether a solid (contaminated with drilling fluid cement, lightweight cement or formation) or a liquid (drilling fluid) fills the annular space.

4.1.3 New Generation Ultrasonic Tool

A recent development in ultrasonic technology addresses the limitations of USIT. The new generation tool combines the traditional ´pulse-echo´ technique with flexural wave imaging.

The new generation ultrasonic tool includes a rotating subassembly supporting four transducers (Fig. 25). A normally aligned transducer is positioned on one side of the tool for generating and detecting the ´pulse-echo´. The other three transducers are on the opposite side of the tool and are aligned at angle. One of these transducers transmits a high-frequency pulsed beam around 250 kHz to excite a flexural mode in the casing. This mode transfers acoustic energy into the annulus. The energy reflects at the interfaces with an acoustic contrast, for instance, interface of the casing and the shale formation. It propagates back through the casing primarily as a flexural wave to reradiate energy into the casing fluid (Bellabarba, et al. 2008).

This base of work principle is the 'pitch-catch' technique. Processing the resulting logs provides information about the type and acoustic velocity of the material filling the annulus, the casing position and the geometrical shape of the borehole (Bellabarba, et al. 2008).

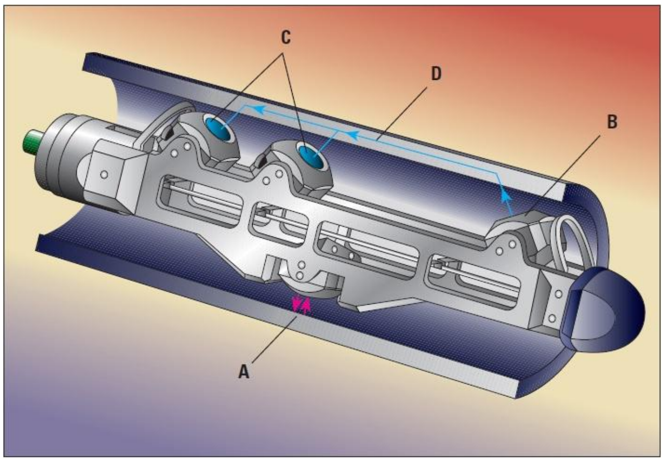


Figure 25: Isolation Scanner subassembly.

The first objective of processing logs is to obtain a robust interpretation of the material type immediately behind the casing. The inputs to this processing sequence are the material acoustic impedance and the flexural-wave attenuation derived from the amplitude of the casing arrivals on two receivers.

The output of measurements is a solid-liquid-gas (SLG) map shown in Figure 27 displays the most likely material state behind the casing. Axes on the SLG map are a flexural-wave attenuation in dB/cm of the first casing arrival estimated at two receivers and a 'pulse-echo' impedance in Mrayl.

In addition to the material behind the casing assessment, the second objective of processing is to extract relevant information from third-interface reflection echoes (TIEs) generating from the annulus/formation interface and further characterize the material filling the annulus (Bellabarba, et al. 2008).

In Figure 26 the work principles of USIT and Isolation Scanner is shown. Here is a signal propagation for the ´pulse-echo´ technique denoted in red and from a transmitter to a receiver for the flexural-wave pitch-catch technique denoted in blue. A typical waveform from the latter technique composes of the casing arrival and TIEs.

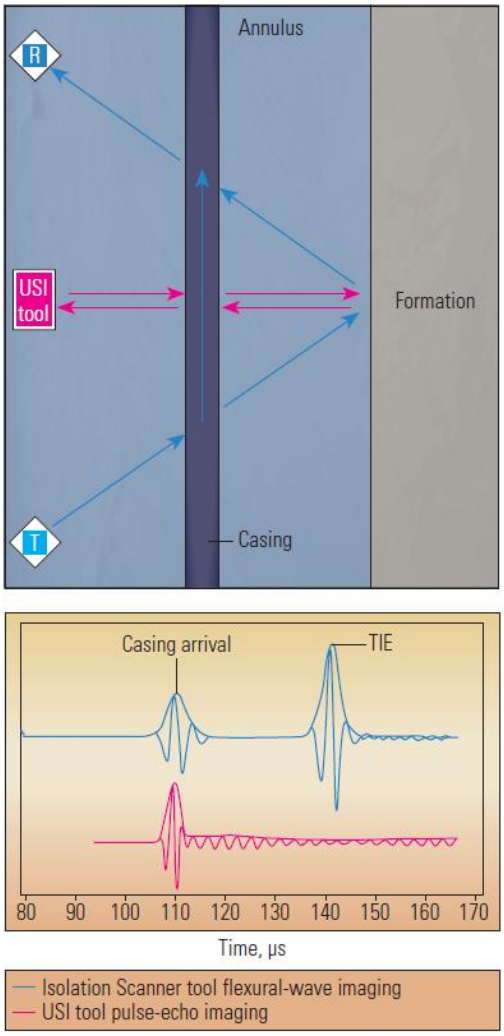


Figure 26: Difference in USI measurements and Isolation Scanner flexural-wave imaging (Bellabarba, et al. 2008).

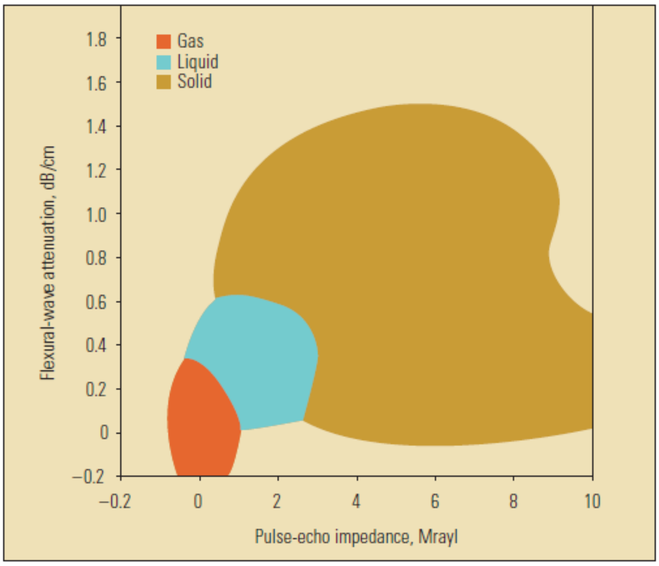


Figure 27: Solid-liquid-gas for a Class G cement (Bellabarba, et al. 2008).

Field data shows that shale creep occurs naturally with a variable speed and does not always require activation. It takes some time for barriers to form, and time is counted in weeks or months. During this period the annulus closure should be inspected. Several CBL runs at different dates after the well was drilled, also called time-lapse bond logging, have been performed in a number of wells at the Valhall field. A new generation ultrasonic tool was run into wells, and the SLG maps as outputs were obtained. In Figure 28 it is well seen the progression of the annulus closure within two months. The barrier had not been activated, and it was the naturally occurred shale barrier (Kristiansen, Delabroy, et al. 2021).

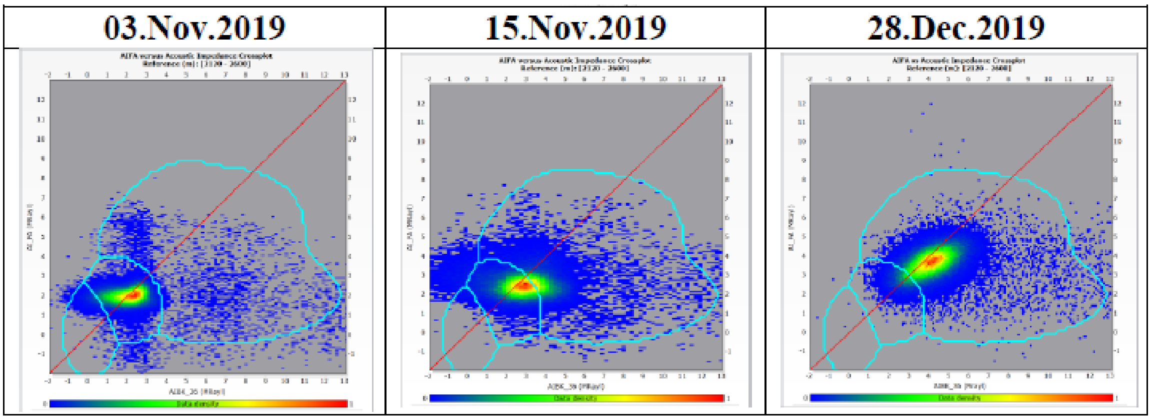


Figure 28: Example of time-lapse sonic measurements across Horda 2 Formation (Kristiansen, Delabroy, et al. 2021).

4.1.4 Logging through Tubing

The challenge today is to assess before the end of the well production life, if the formation behind the casing has closed or not. The formation barrier around the well in uncemented or poorly cemented sections can occur naturally during the well lifetime, and this seal can be identified with the bond logging. Bond logging is challenging in production wells due to the tubing installed. This tubing should be pulled out since conventional bond logging tools require unimpeded access to the casing. This requires removing the tubing with a rig.

A novel methodology and a logging tool have been presented on the market as a prototype. It advertises the possibility of assessing cement bond around the casing through the production tubing. The work principle is the same as for the CBL tool, however the signal weakens more than usual because of the presence of the tubing inside the well. The smaller bonding signal is then identified through unique frequency domain signal processing (Zhang, et al. 2019).

A joint project on the multi-string cement bond tool was launched in October 2016. The first feasibility phase with experimental studies was confirmed in July 2017. By the end of this phase, a series of practical theories and processing algorithms were developed. In October 2017, two prototype Multi-String Isolation Logging (MSIL) tools were shipped to the UK for offshore field tests. The logging results within tubing are compared after tubing is pulled out using various third party traditional CBL and USI tools.

To evaluate the cement bond behind casing with production tubing in place is problematic. The E_1 arrival amplitude is eventually undetectable. Due to the presence of tubing, two extra fluid-steel interfaces appear and highly attenuate the acoustic energy when the signal goes through the tubing back and forth to the casing, the cement sheath and the formation. It can be explained by Figure 29, where R is the reflection coefficient proportional to the acoustic impedance contrast. The resulting high acoustic impedance contrast at boundaries results in the energy attenuation (Zhang, et al. 2019).

The reflection coefficient describes how much of a wave is reflected by an impedance discontinuity in the transmission medium, and it is calculated with Equation 7.

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{7}$$

The transmission coefficient describes the amplitude of a transmitted wave relative to an incident wave amplitude, and it is calculated with Equation 8.

$$T = 1 + R = \frac{2 \cdot Z_2}{Z_2 + Z_1} \tag{8}$$

where Z_1 is the specific acoustic impedance of the first medium and Z_2 is the second medium's acoustic impedance in [Pa·s/m] or in [rayl].

The acoustic impedance is the absorption of sound in a medium, equal to the ratio of the sound pressure at a boundary surface to the sound flux through the surface. The sound flux is expressed as the flow velocity of the particles or volume velocity multiplied by the surface area. The acoustic impedance at a particular frequency indicates how much sound pressure is generated by a given acoustic flow.

$$Z = \frac{p}{U} = \rho \cdot c \tag{9}$$

where p – the acoustic pressure in the medium in [Pa]; U – the sound flux in [m^3/s]; ρ – the volumetric density of the medium in [kg/m^3]; c – the speed of the sound waves in [m/s].

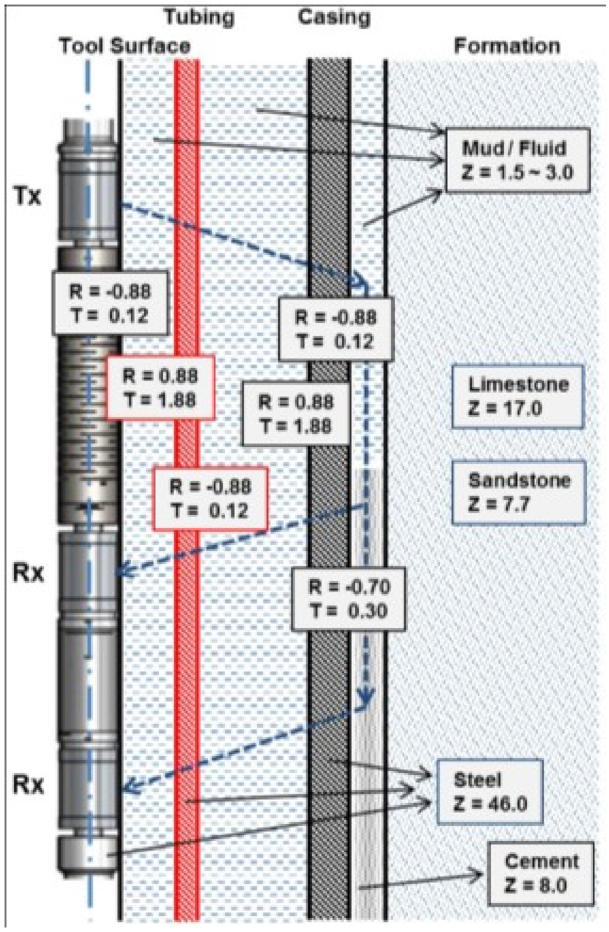


Figure 29: Acoustic wave reflection and transmission within a tubing and a casing (Zhang, et al. 2019).

The outgoing wave through tubing has a total transmission coefficient of:

$$T_{tub} = 1.88 \cdot 0.12 = 0.23$$

The incoming wave back from the casing-cement interface will go through the same attenuation again. The extra loss caused by the tubing inefficiency is equal to (Zhang, et al. 2019):

$$Loss = 1 - T_{tub}^2 = 95\%$$

MSILT has the transmitter and two receivers at 3 ft and 5 ft away from the transmitter. To address challenges, the tool was redesigned. The existing radial cement bond tool has a 3½′′ outer diameter (OD) to maximize the acoustic power output from an optimized transmitter. A single crystal replaces the 3 ft radial sensitive receiver to provide the best signal-to-noise ratio (SNR). The driving and receiving electronics has been modified during the development through iterations.

This new technology is not commercialized yet and requires improvements. However, logging through tubing has great potential since it can evaluate the environment behind the casing without first pulling the tubing. Usually, there is a short time between logging operations after the tubing is pulled and well abandonment operations. That’s why Company elaborates the main and the backup abandonment plan in advance. By logging through the tubing, there is sufficient time before P&A

activities to decide upon which P&A method to apply and develop a proper well abandonment plan knowing the condition behind the casing.

4.2 Pressure Testing

Once an acceptable bond quality (see Section 4.2) was defined over a sufficiently long interval, direct physical testing should be performed.

As mentioned previously, the seal formation shall have the required adequate fracture strength to withstand the anticipated future pressures. Pressure testing aims to confirm if the calculated stress model correlates with the measured formation strength and ensure the seal around the casing and the absence of channels between the casing and the formation.

The procedure to test the potential formation barrier is described as follows:

1. The casing is perforated to gain access to the shale formation behind the casing. The distance *L* between upper and lower perforations is established by Company depending on the barrier extension requirement (Fig. 30). According to NORSOK D-010 (2021) and O&G UK Guideline (2018), this distance should be no more than 30 m MD long, and according to NOGEPA Standard Nr. 45 (2021), the distance shall be no more than 50 m MD long.
   From published works, it is known that the potential barrier section is pressure tested by perforating approximately 10 m below the top and 10 m above the base of this section (Williams, et al. 2009).
2. Running a test string. The packers are installed as in Figure 30. It is also possible to monitor the pressure gauge on the surface without installation the packer above the upper perforation (Stokkeland, et al. 2020).
3. Solid free fluid is pumped into the test string and through the deepest perforations. The smaller the volume between the packers and in the pipe, the more accurate are the results. If there is no pressure increase observed in the upper set of perforations or the casing annulus in case of an absence of the upper packer, the barrier is accepted.
4. Volumes pumped through the test string is interpreted to represent Formation Integrity Test (FIT).
5. Afterwards, a technical limit test can be performed to prove that the formation is strong enough to withstand the potential influx of hydrocarbons coming up from below. The limit test should be consistent with previous knowledge for this formation and indicate that an annular barrier formed.

Company decides itself which test to perform: Pressure Integrity Test (PIT) or FIT, Leak-Off Test (LOT) or Extended Leak-Off Test (XLOT); the latter is not preferable test as the formation is fractured. The purpose of testing the well barrier is to test until the predetermined anticipated pressure is required to withstand formation.

All tests above listed can be performed if there is an annular seal. If the pressure is not transmitted between lower to upper perforation than we can measure the actual strength of the formation that crept into the annulus. The strength of formation having crept will be different from the formation strength of the virgin formation. Understanding the formation strength is important to assess if the new formation closing around the pipe can withstand the Maximum Annulus Pressure given by the reservoir fluid migrating up along the pipe annulus and expanding till below the SAAB element. Rock mechanical data shall be systematically obtained to ensure well integrity in the well construction, operational and abandonment phases. The common methods are listed in Table 3. The formation integrity requirements are presented in Appendix A.

Method	Objective	Comment
PIT/FIT	To confirm that the formation/annulus cement is capable of supporting a pre-defined pressure	Application of a pre-determined pressure to the formation and observe if stable
LOT	To establish the pressure that the wellbore wall/annulus cement can support	The test is stopped once a deviation from the linear pressure vs. volume/time is observed
XLOT	To determine the minimum in-situ formation stress	The test propagates a fracture into the formation and establishes the fracture closure pressure (FCP)

Table 3: Methods for determining formation integrity [Table 2 from (NORSOK 2021)].

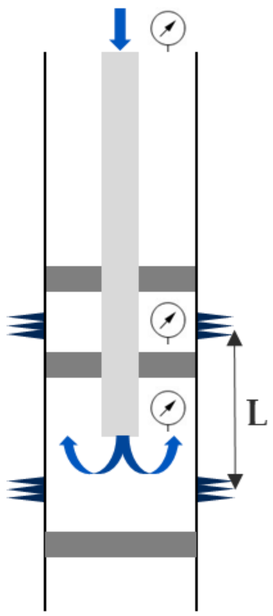


Figure 30: Setup for pressure testing of a shale barrier, often referred to as a communication test (Kristiansen, Delabroy, et al. 2021).

An innovative one trip solution has been developed for the hydraulic verification of the barrier to reduce the amount of runs in the wellbore (Stokkeland, et al. 2020).

The way the system is build up shown below. It is equipped with a disconnect tool at the top of the BHA, a dual cup system with an integrated bypass and a ball seat assembly below cups to divert the flow (Fig. 32). Tubing Conveyed Perforating (TCP) system has a firing head and one gun carrier with 1 ft loaded with 12 shots per foot in the top and 1 ft loaded in the bottom of a typical 30 m interval (Stokkeland, et al. 2020).

Figure 31: FIT assembly including TCP guns (Stokkeland, et al. 2020).

Firstly, the 9 5/8´´ Formation test tool is deployed with a 9 5/8´´ Retrievable Bridge Plug (RBP) to a desired depth.

The next step is the perforation process. The TCP perforating gun is activated by dropping a 1´´ activation ball and then pressuring up the inside of the string to a detonation pressure. A flow check is performed to confirm the stability of the well.

The next step is the activation of the FIT tool. The activation ball for the tool is dropped to divert the flow between the dual swab cups and isolate the assembly below the cups. An integrity test of the tool should be then performed in the empty casing string to verify the system's integrity. Afterwards, the testing of the formation can be started.

The final step is to pump cement on top of RBP through the 3´´ inside diameter running tool.

The procedure is described in detail in the work of Stokkeland, et al. (2020) and depicted in Figure 32.

Figure 32: FIT operational procedure (Stokkeland, et al. 2020).

4.3 Shale Barrier Verification Procedure

The result of this study is an elaboration of a general workflow to provide an understanding of the process of evaluating the shale barrier presence and quality during different well phases: construction, intervention and P&A. The roadmap was developed to ensure correspondence to the relevant national regulations on formation annular barriers mentioned in Section 2.3.

First of all, the criteria for acceptable formation annular barriers for bond logging will be described. It implies the tool selection, processing the primary data and, finally, interpreting the acoustic log data obtained. The first stage requires assembling two independent logging tools for the bond between casing and formation that can be deployed in one run.

Well logging involves the sequential execution of operations that ensure the primary data acquisition, and it includes:

- selection of logging tools or a combined assembly of modules;
- testing and field calibrations of tools before logging;
- tripping in/out operations and registering log responses;
- testing and field calibrations of tools after logging, if it is necessary.

Threshold values and some features of acoustic data have been determined for shales by laboratory studies of core plugs and samples (Lavery, Jambunathan und Shafikova 2019).

- The attenuation amplitude of the signal measured by CBL tool varies from 10 mV to 20 mV.
- The acoustic impedance of shale rock is in the range 3.68–12.60 Mrayl depending on the bulk density 2.3–2.8 g/cm^3.
- Low contrast casing signal and clear formation arrivals are on the VDL diagram.
- An increase in the casing ovality across from the shale formation is a result of in-situ stress differences.

  The following equation calculates the ovality:

  $$Ovality = \frac{D_{max}}{D_{min}} - 1 \tag{10}$$

  where D_{max} is the maximum measured diameter in [in] and D_{min} is the minimum measured diameter in [in].
- The formation features in the form of sinusoids on acoustic impedance images it is rarely encountered though.
- Absence of TIEs measured by an ultrasonic flexural-wave imaging tool.
- The obtained values should be in the solid phase on the SLG map.

If received signals from the well logging measurements correspond to the ranges of critical values, then the quality of the bond between the casing and the shale formation is sufficient. The decision tree for the interpretation of verification of the shale barrier is presented in Figure 33, where all critical values of log responses are depicted.

As previously described, the regulations require that the criteria for acceptable formation annular barriers be established before logging; the road map achieves this objective for the case of formation in the annulus. This roadmap starts with the division of the formation barrier into the naturally occurred and artificially stimulated. Afterwards, the bond logging measurements are required by two independent tools. As a CBL-VDL tool regularly is run, the evaluation of the CBL amplitude and Bond Index are mandatory. In the case of the radial tool deployment, the CBL amplitudes are acquired in each segment. And the second confirmation by another independent bond logging is required; in this case, it is the ultrasonic logging tool. The measurements acquired by two logging tools should not contradict, on the contrary, should supplement each other. Also, the presence of shale behind the casing can be confirmed by some other indicators depicted in white rhombs in Figure 33. Still these indicators are auxiliary and may not be encountered at all.

If the accumulated barrier length fulfils the local requirements and a shale formation has previously been classified as a barrier within the actual field, the formation barrier is verified. If the pressure testing has not been performed for the target shale formation or the bond logging is not conclusive, the auxiliary procedure of pressure testing is required. And only after the successful results of physical testing, the shale-as-a-barrier can be verified and utilized for well isolation purposes.

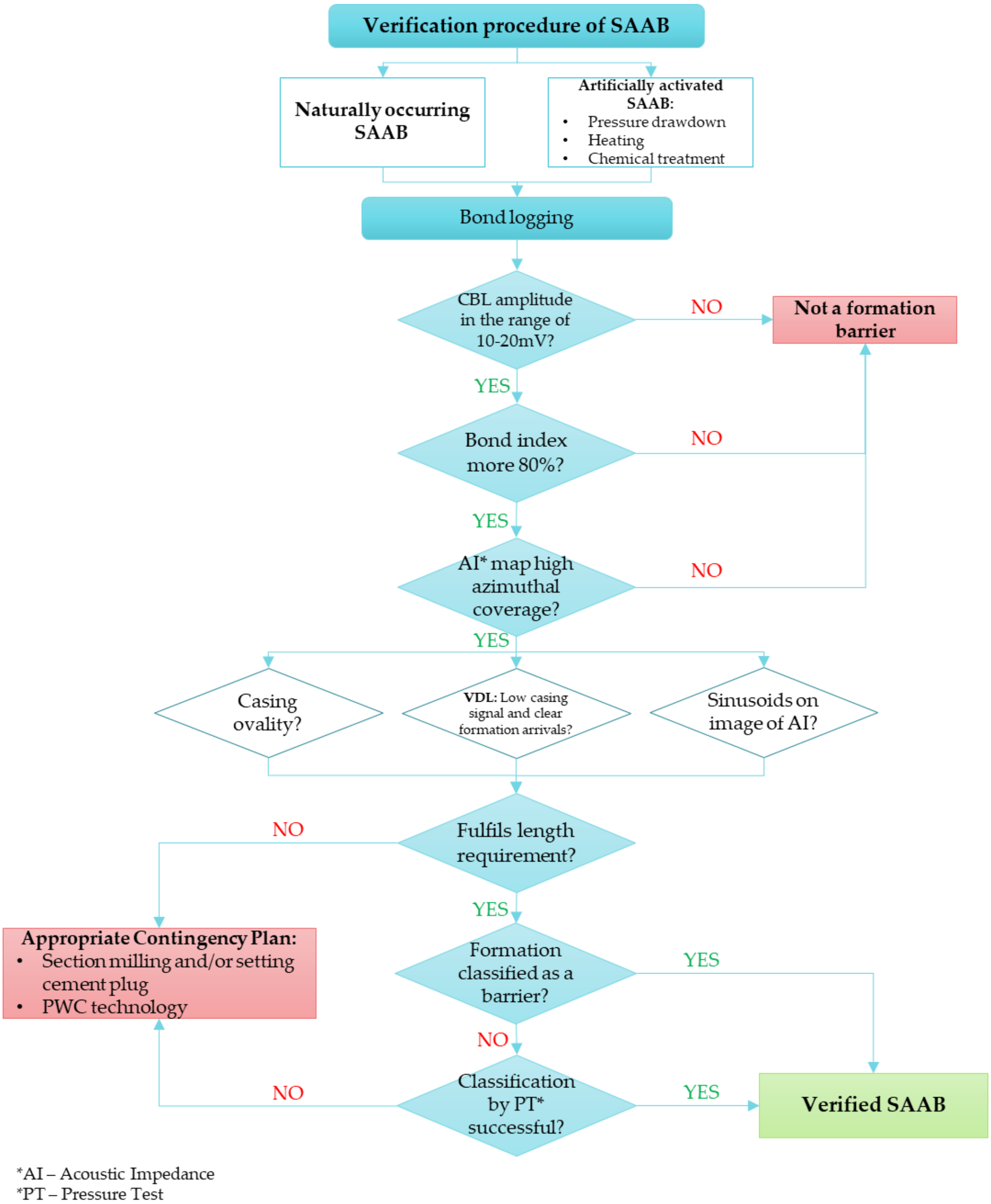


Figure 33: The roadmap of P&A operations using SAAB technology.

Chapter 5 Conclusion

The main objective of this work was to provide an overview of the SAAB technology that was extensively used in the last 15 years in the North Sea oil and gas region.

SAAB technology has been endorsed in the North Sea region, particularly in the Norwegian and UK continental shelves. Wintershall Dea has accepted this technology in more than 40 wells in Norway. The Business Unit Germany of Wintershall Dea is currently working on the acceptance of the technology at the State level.

Ultimately, mobile sealing formations are of great interest for the permanent abandonment of oil wells. Shales are known to be cap-rocks, so they have all properties necessary for sealing the annulus: impermeable, low gas leakage rate compared to Portland cement material, low susceptibility to chemical aggressive media (hydrogen sulfide and carbon dioxide) and ability to close cracks (self-healing) that may occur over time.

The well abandonment phase includes two stages: pre-planning, or engineering stage, and execution stage. The first stage requires gaining a set of information regarding the specific requirements stated in the local regulations and national standards and the shale characterization. At present, this alternative technology is not accepted in all countries of the North Sea region. The current regulations and standards might be a challenge for the initial technology deployment. The new technology is fully covered by NOGEPA Standard Nr. 45, NORSOK D-010 Standard and O&GUK Guidelines.

The further challenge that may emerge, especially in old wells, is to collect all necessary critical information about the shale characterization. Possible attributes that could be evaluated from cutting/core data and open-hole logging data are porosity, permeability, mineralogy, unconfined strength and friction angle. The most eligible shale for barrier forming is porous, low permeable rock with more than 40 % clay content and cementing minerals less than 25 %.

Normally shale core samples would not be available, whereas log data might be. High porosity (low density), high clay content and low acoustic velocity can be used as indicators of a potential barrier. If a formation barrier has already been qualified within this field, characterization data could be used to reference the subsequent wells.

Another required crucial information is the previous bond logging data, if SAAB is detected during the well intervention or P&A phase. Even threshold values such as CBL amplitude, acoustic impedance and velocity are determined and known if the annulus is sealed with the formation and not with the cement. Still some challenges may appear due to the physical and mechanical properties alteration of the casing, formation and fluid filling the well.

New lab tests to measure shale creep have been developed in recent years; these tests can be carried out on shale core plug samples if they are available. Ultrasonic measurements in a laboratory may help understand the mechanisms driving the formation of shale barriers and distinguish between barrier-forming and non-barrier forming shales.

Historical annulus pressure test data is of interest as well since results can be compared and information about the formation can be updated. The question regarding the number of positive confirmations of SAAB by pressure testing is still under dispute. It was discussed that an optimal number of successful tests might be three (Stokkeland, et al. 2020). However, each Company has the possibility to establish a sufficient number of pressure tests. For instance, BU Germany is interesting not to perform pressure testing as the local authority does not require it.

Information regarding the local legislation, the shale characterization, open-hole and cased-hole logging data and results of previous pressure tests determine the strategy for the potential adoption of shale as the well barrier.

The estimation of time spent on P&A using SAAB is individual for each well and depends on when SAAB will be applied. The most common cases are listed below.

- A sealing formation can be activated during the well construction phase through the pressure drop in the annulus, heating and chemical treatment of the shale formation.
- The sealing formation can occur naturally during the well lifetime in the annular space, which is uncemented or poorly cemented.
- It can be activated during the well P&A phase.

Annulus closure can be induced by annulus pressure reduction and facilitated either thermally or chemically. A variety of displacement mechanisms; however, the creep contributes up to 90 % to the formation deformation, and intuitively, to obtain a good seal, the ductile mode of failure is preferable to the brittle mode.

Accelerating creep has so far been achieved by performing a rapid pressure drop in the annulus during the well construction phase (Kristiansen, Delabroy, et al. 2021). The thermal stimulation and chemical treatment of the shale rock have been delivered only in lab conditions.

The second stage of the well abandonment phase is the execution. The optimal sequence of the information acquisition and the abandonment plan execution are as follows:

1. Open-hole logs and core data analysis of the potential formation obtained from different wells within the same field.
2. If the formation has met the primary indicators regarding the shale characterization, the bond logging should be conducted to detect whether this barrier has formed naturally or requires activation.
3. And last but not least, the pressure testing will finally verify or not the shale barrier.

The local legislation dictates the barrier extension requirement, which varies from 30 m to 50 m. The contact between the casing and the formation shall be verified with two independent logging measurements with an azimuthal coverage of the wellbore walls.

The pressure test shall be implemented in a certain number of wells per field to verify the hydraulic isolation consistently.

It was comprehensively discussed in this thesis that time-lapse bond logging can be highly beneficial to catch the shale movement, although it has been done during the well construction phase only. However, as the logging-through-tubing technology has been maturing, it will be possible to monitor the shale movement without pulling out the tubing.

If Company decides to activate the shale displacement, additional lab tests and numerical modelling should be considered. The detailed experimental study into the effect of annular condition changes is recommended as the continuation of this master thesis.

Chapter 6 Further Recommendations

This thesis was proposed to familiarize Wintershall Dea's specialists and engineers with the SAAB technology. For deeper learning and understanding, it is recommended to dive into the following topics:

1. Conducting laboratory experiments such as Shale Barrier Test to evaluate the creep rate on core samples taken from the Tertiary Middle North Sea Group.
2. Lessons Learned on the basis of existing experience within Company.
3. Sonic logging technologies to detect the formation barrier.
4. Pressure testing and its procedure, particularly for Wintershall Dea.

This list can be expanded; however, these are the first steps for considering this technology to be applied in future in Company.

Appendix A Acceptance Criteria for SAAB

Acceptance Criteria for Creeping Formation

The application of creeping formation as an external WBE shall meet the requirements defined in Table 4.

Features	Acceptance criteria
A. Description	The element consists of creeping formation (formation that plastically has been extruded into the wellbore) located in the annulus between the casing/liner and the borehole wall.
B. Function	The purpose of the element is to provide a continuous, permanent seal along the casing annulus to prevent flow of formation fluids and to resist pressures from above and below.
C. Design, construction and selection	1. Consideration of a formation as a WBE applies when the formation is known to have plastic properties and can be expected to form a seal with acceptable integrity towards axial leakage. 2. The element shall be capable of providing an eternal pressure seal: a) The formation interval shall be geologically homogeneous and laterally continuous. b) Creeping formations include any low permeability formations which are sufficiently mobile to allow rapid closure of cracks such as claystone, shale and salt. Typical formation characteristics: low permeability, ductile, high smectite and clay content or salt, low content of cementing materials (quartz, carbonates etc.), low friction angle, low cohesion, and low unconfined compressive strength (UCS). c) Permeable and non-mobile formations such as silt, sandstone, limestone, basalt, and granite are excluded. 3. The minimum cumulative formation interval shall be 30 m MD for a qualified WBE and 2x30 m MD if it part of the primary and secondary well barrier. 4. The minimum formation stress at the base of the

	element shall be sufficient to withstand the maximum pressure that could be applied.
D. Initial test and verification	1. Position and length of the element shall be verified by bond logs: a) Two independent logging measurements/tools shall be applied. Logging measurements shall provide azimuthal data. b) Logging data shall be interpreted and verified by qualified personnel and documented. c) The log response criteria shall be established prior to the logging operation. d) The minimum contact length shall be 30 m MD for a single WBE or 2x30 m MD when the same formation will be a part of the primary and secondary well barrier, with azimuthal qualified bonding. 2. Pressure integrity shall be verified by application of a pressure differential across the interval. The interval should be no more than 30 m MD long. 3. Formation integrity shall be verified according to 'Formation integrity requirements' Table 5, in order to qualify as a WBE. The results should be in accordance with expected formation stress from the field model. 4. If the specific formation is previously qualified by logging and FIT, logging is considered sufficient for subsequent wells. Differential pressure testing is required if the log response is not conclusive or there is uncertainty regarding geological similarity.
E. Use	The external WBE is mainly applied in a permanently abandoned well.
F. Monitoring	None
G. Common well barrier	None

Table 4: Creeping formation [Ref.: (NORSOK 2021), EAC Table 52].

Formation Integrity Requirements

As it is said above that formation integrity shall be verified by means of FIT and LOT as the creeping-in formation strength differs from the initial formation strength prior to the shale displacement. The minimum formation requirements are listed in Table 5.

Well type/activities	**Minimum formation integrity**	
	New wells (after D-010: 2013 rev 4)	**Existing wells (before D-010: 2013 rev 4)**
Exploration wells – all activities including permanent abandonment	Formation pressure integrity can be verified by FIT or LOT. The measured values shall be sufficient for required kick margin, for dynamic kill of a blowout through relief well and for permanent abandonment.	
Production wells – drilling activities and activities with mud in hole		
Production wells – completion activities with solid-free fluid, production/injection and abandonment activities	Minimum formation stress/FCP shall exceed the maximum wellbore pressure at formation depth.	The formation integrity pressure (in the interval between Leak-Off Pressure (LOP) and FCP) used in the original design may be used. The original design values shall be re-assessed prior to permanent abandonment of wells.

Table 5: Formation integrity requirements [Ref.: (NORSOK 2021), Table 3].

It is shown the difference between pressure tests in Figure 34. It is very important that any FIT/LOT/XLOT never exceeds a pre-defined pressure limit which shall be determined in the detailed drilling guidelines and confirmed in the standing instructions.

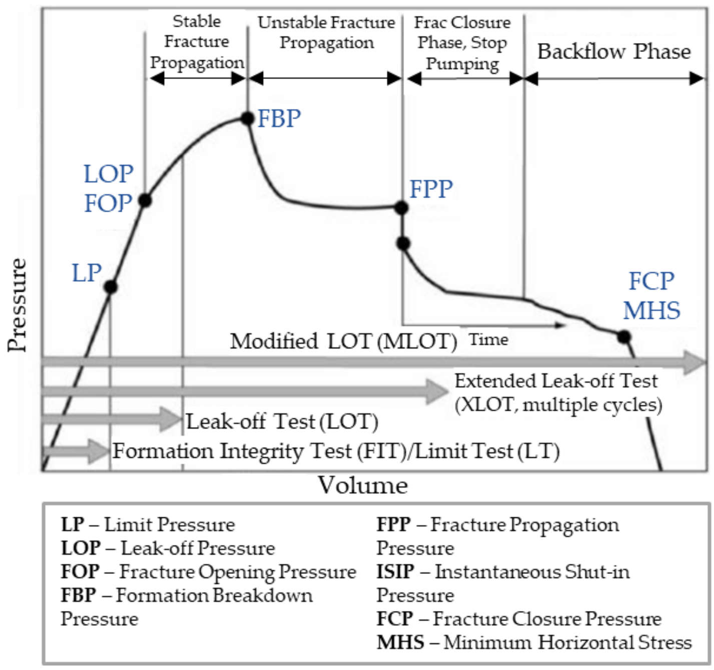


Figure 34: Pressure testing diagram.

Appendix B Experimental Work Plan for Formation Type Barrier

Experimental Work Plan

Here is presented the program of measurements and tests in order to evaluate the suitability of creeping formation as a well barrier (Table 6).

A requirement classification (1 to 3) is provided where:

1 = mandatory; 2 = recommended; 3 = not applicable.

Property	Require-ment	Test	Ageing required?	ACCEPTANCE CRITERIA	
				Before ageing	After ageing
PERMEATION TESTING					
Nitrogen permeability	1	See 3.3.2	Yes	<0.03 m^3/year , but no more than 10 µD	<50 % increase
Diffusion coefficient	3	-	-	-	-
INTERACTION WITH FLUID					
Dry mass	1	Measurement of mass after drying to constant mass at 105 ºC	Yes	-	<3 % loss in dry mass relative to that before ageing
Absorption	3	-	-	-	-
DIMENSIONAL STABILITY					
Expansion/Swelling					
During hardening	3	-	-	-	-
Hardened	2	ISMR Suggested Method	-	-	-
Shrinkage					
During hardening	3	-	-	-	-
Hardened	2	ISMR	-	-	-

		Suggested Method			
Differential thermal expansion	2	ASTM E228	No	-	-
Creep	2	ASTM C512-10	Creep rate determined by application	-	-
MECHANICAL TESTING					
Triaxial testing	2	ISMR Suggested Method	Yes	-	-
Cohesion	2		Yes	-	-
Poisson's ratio	2		Yes	-	-
Internal friction angle	2		Yes	-	-
Hydrostatic compressive field	2		Yes	-	-
UCS	2	ISMR Suggested Method	Yes	-	-
Tensile strength	2	ASTM C496	Yes	-	-
Elastic modulus	2	ASTM C469	Yes	-	-
Hardness	3	-	-	-	-
OTHER CHARACTERISTICS					
Bond strength					
Shear bond strength	3	-	-	-	-
Tensile bond strength	3	-	-	-	-
Decomposition temperature	3	-	-	-	-
Density	3	-	-	-	-
Stress relaxation	3	-	-	-	-

Table 6: Experimental work plan for Type F (Formation) materials (Oil & Gas UK 2015).

Appendix C The Hordaland Group Shale Properties

The North Sea Lark-Horda Shale Properties

The relevant mineralogy of the North Sea Lark-Horda shale is shown in Table 7 and mechanical properties – in Table 8. CEC value is in the range of 55 – 80 meq/100g.

Non-clay mineralogy	
Quartz	19-21 %
Pyrite	5-9 %
Carbonates (Calcite and Dolomite)	1-2 %
Trace minerals (K-Feldspar, Plagioclase; Apatite)	1 %
Clay mineralogy	
Smectite	3-4 %
Illite/Smectite	9-12 %
Illite/Mica	37-40
Kaolinite	18-21 %
Chlorite	1 %

Table 7: The Lark-Horda formation mineralogy (van Oort, et al. 2020).

Parameter	**Value**	**Units**
Young's modulus, *E*	120 000	psi
	827.4	MPa
Poisson's ratio, *ν*	0.27	-
Cohesion, S_0	857	psi
	5.7	MPa
Friction angle	4.3	deg
Dilation angle	ND	deg
Creep model parameter, C_1	$1.7 \cdot 10^{-6}$	-
Creep model parameter, C_2	1.7	-
Creep model parameter, C_3	-0.641	-

Creep model parameter, C_4	0	-

Table 8: The Lark-Horda formation mechanical properties (van Oort, et al. 2020).

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Acronyms

CBL	Cement Bond Log
CEC	Cation Exchange Capacity
CEL	Cement Evaluation Logging
CT	Computer Tomography
DEA	Danish Energy Agency
DEPA	Danish Environmental Protection Agency
DNV	Det Norske Veritas
DSA	Danish Subsoil Act
DWEA	Danish Working Environment Authority
ESG	Environmental, Social and Governance
GL	Germanischer Lloyd
FCP	Fracture Closure Pressure
FIT	Formation Integrity Test
ISO	International Organization for Standardization
LOT	Leak-Off Test
MPE	Ministry of Petroleum and Energy
MSIL	Multi-String Isolation Logging
NCS	Norwegian Continental Shelf
NOGEPA	Netherlands Oil and Gas Exploration and Production Association
NORSOK	Norsk Sokkels Konkuranseposisjon
NPD	Norwegian Petroleum Directorate
OD	Outer Diameter
O&G UK	Oil and Gas UK
OBM	Oil Base Mud
P&A	Plug and Abandonment
PIT	Pressure Integrity Test
RBP	Retrievable Bridge Plug
SAAB	Shale as a Barrier
SCMT	Slim Cement Mapping Tool
SEM	Scanning Electron Microscopy

SLG	Solid-Liquid-Gas
SNR	Signal to Noise Ratio
TCP	Tubing Conveyed Perforating
TIE	Third Interface Echo
TOC	Top of Cement
TOC	Total Organic Carbon
TOT	Tetrahedral-Octahedral-Tetrahedral
UCS	Unconfined Compressive Strength
UK	United Kingdom
UKCS	United Kingdom Continental Shelf
UNEP	United Nations Environment Programme
USIT	Ultrasonic Imager Tool
VDL	Variable Density Log
WBE	Well Barrier Element
WBM	Water Based Mud
XLOT	Extended Leak-Off Test
XRD	X-ray Diffractometry
XRF	X-ray Fluoroscopy

Symbols

$\Delta\Pi$	osmotic potential	[J/l]
α_T	coefficient of linear thermal expansion	[°C^{-1}]
ε_a	axial thermal strain	[mm/mm]
ε_{vol}	volumetric strain	[%]
φ	total porosity	[%]
ρ	volumetric density of the medium	[kg/m^3]
σ_a	axial thermal stress	[MPa]
σ	membrane efficiency	[-]
a_w	chemical activity of water	[-]
C	creep parameter	[%]
c	speed of sound waves	[m/s]
E	Young's modulus	[MPa]
P	acoustic pressure in the medium	[Pa]
R	molar gas constant	[J/mol·K]
R	reflection coefficient	[-]
T_{abs}	absolute temperature	[K]
T_1	final temperature	[°C]
T_0	initial temperature	[°C]
t	time	[hour]
T	transmission coefficient	[-]
T_{tub}	transmission coefficient through tubing	[-]
U	the sound flux	[m^3/s]
UCS	unconfined compressive strength	[MPa]
V_p	compressional velocity	[km/s]
V_w	molar volume of water	[l/mol]
Z	specific acoustic impedance	[Pa·s/m], [rayl]

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