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Abstract

Today there are 6944 wells drilled on the Norwegian Continental Shelf (NCS) [3]. All of these wells have to be permanently plugged and abandoned in the future. This will come at an estimated cost of £35- £104 billion (410-1200 billion NOK) [2]. Plug and abandonment (P&A) is therefore a costly liability for oil companies on the NCS, and a focus has been on reducing cost of permanent plug and abandonment (PP&A). The standard NORSOK D-010 is used for the requirements of well integrity in drilling and well operations, which also include PP&A. The length requirements in the standard are based on historic practices. This causes a discussion on these requirements. Creeping shale, shale being a term for argillaceous rocks, is a material that is relatively new to be used as a well barrier element (WBE). The material properties of shale are favorable for use as a barrier. It is also a material that comes with no material cost. In contrast to cement, creeping shale is ductile and will have self-healing behavior. In addition, the permeability of shale can be extremely low, in the nanodarcy scale, 1000 times less than a perfect cement job. This gives ground to allow for a shorter barrier length of creeping shale than the traditional cement.

The debate about continuous versus cumulative verified bond quality is also a hot topic in the industry today. The concept of stacking external barriers is done over an interval where the cumulative length of acceptable bond quality reaches the NORSOK D-010 length requirement. Allowing stacking of barriers over an interval, will reduce risk, cost and time – it will give an even more robust solution.

Acknowledgements

This thesis would not be possible without the guidance of Kjell Kåre Fjelde. I wish to express my deepest gratitude for the motivation and input you provided me with during the strange and restricting covid-19 period. The meetings and conversations we had provided me with great knowledge, and a good plan to complete my bachelor thesis. Thank you so much.

I would also like to thank Per Ove Staveland – Sr. P&A Engineer at Repsol, for guidance, input and sharing his knowledge. The conversations with you were insightful and educational.

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List of Abbreviations

ASV- Annular Safety Valve

BOP- Blowout Preventer

CBL- Cement Bond Log

DS- Drillstring

EAC- Element Acceptance Criteria

FIT- Formation Integrity Test

HC- Hydrocarbon

HP- High Pressure

HSE- Health, Safety and Environment

LOT- Leak-off Test

LP- Low Pressure

MD- Measured Depth

NCS- Norwegian Continental Shelf

PSA- Petroleum Safety Authority

P&A- Plug and Abandonment

PP&A-Permanent Plug and Abandonment

ROI- Return on Investment

TA- Temporary Abandonment

UAC- Upper Accepted Case

WBE- Well Barrier Element

WBS- Well Barrier Schematic

WL- wireline

WH- Wellhead

XMT- X-mas tree

XLOT- Extended Leak-off Tes

1 Introduction

1.1 Background

After decades of production of oil and gas on the NCS, old wells need to be permanently plugged and abandoned. This is a relatively new and costly operation on the NCS. Therefore, some of the requirements in the standard NORSOK D-010 are based on old practices, to make it a one size fits all model. PP&A being a costly project with no return on investment, the focus has been on reducing the cost. With new discovery's the NORSOK D-010 standard is revised to make it attractive to invest in the Norwegian Petroleum sector. In revision 5 of the standard, there was some updates to P&A principles and techniques. The update did however not include stacking, i.e., cumulative length of acceptable bond quality.

Creeping formation is a relatively new barrier material used. Discoveries made about shale's capability to creep have sparked interest to investigate if shale as a barrier can be activated/assisted. Using creeping shale as a Well Barrier Element (WBE) can reduce risk, cost and time.

1.2 Objective of Thesis

The objective of this thesis is to highlight some updates in the new NORSOK D-010 revision 5, and to highlight some principles that were not updated. A focus will be on creeping formation and comparing it to cement. This will be done in order to highlight the contact length required for creeping shale, and that a reduced length may be an option.

The principle of stacking will be highlighted. Stacking of external well barriers will reduce the risk, cost and time of PP&A, as there would no longer be a requirement of section milling or PWC. The principle of stacking will be shown in an example well.

1.3 Structure of Thesis

The thesis starts with an introduction to plug and abandonment (P&A). Cost, statuses and P&A phases will be explained. Onwards, a chapter about well barriers will be presented. In this chapter there will be a focus on the requirements and verification of well barrier elements (WBE) as per the new NORSOK D-010 revision 5 standard. A chapter about barrier material will also be presented, with focus on creeping formation and if it is possible to activate/assist the creep rate. Challenges and remedies in P&A are of great interest and the most common challenges/remedies will be presented. Onwards, a discussion follows regarding required continuous length for well barriers. The discussion revolves around reduced required barrier length. In addition, the principle of stacking WBE's will be introduced. Before the conclusion, an example well to be permanent plugged and abandonned will be presented. The new principle of stacking will be used in order to PP&A the example well. At the end of the thesis an argument will be made for input for the next update of the NORSOK D-010 standard, with a focus on creeping formation, reduced barrier length and the principle of stacking WBE's.

2 Plug and Abandonment

Decommissioning of wells, referred to as Plug and Abandonment (P&A), is a challenging and costly operation in the Petroleum industry where a well is temporarily or permanently plugged. The decision to permanently plug and abandon (PP&A) a well is done when a well is depleted, no longer is economically feasible or the well suffers from well integrity issues. The main objective with PP&A is to restore the caprock function to prevent leakages from possible inflow-zones, reservoir and/or permeable zones. To restore the caprock function, Well Barrier Elements (WBE) are combined and verified to become a well barrier envelope.

On the Norwegian Continental Shelf (NCS) the standard issues a two-barrier concept where each barrier must be a cross sectional barrier as shown in figure 2.1 and 2.2.

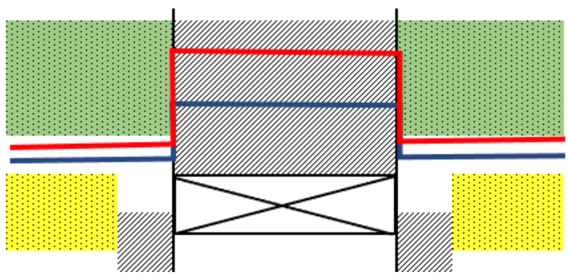


Figure 2.1 Two Barrier Philosophy

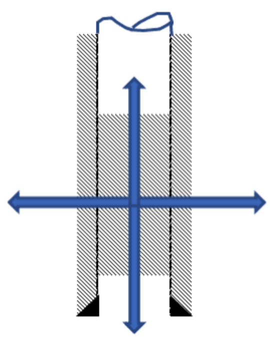


Figure 2.2 Cross-Sectional Barrier

Figure 2.1 is an example well where the primary barrier envelope is marked in blue, and the secondary barrier envelope marked in red. Figure 2.2 illustrates the cross-sectional barrier and that barriers shall be designed to tolerate both horizontal and vertical stresses.

All permanently abandoned wells on the NCS shall be plugged with an eternal perspective. It shall also take into account any foreseeable injection, drainage, chemical and geological processes that may have an effect on the abandoned wells integrity. [1]

2.1 P&A Statuses

There are three statuses in abandonment; suspension, temporary abandonment or permanent abandonment.

2.1.1 Suspension

Suspension is a well status when well control equipment has not been removed and well activities have been paused due to the need of integrity work. Reasons for this could be waiting on equipment, weather, workover on another well etc. In NORSOK D-010 Chapter 10.4.3 it states: *"Well barriers and WBE material(s) shall have sufficient integrity to meet the suspension period, including contingency [1]"*

2.1.2 Temporary abandonment

Temporary Abandonment (TA) involves removal of well control equipment, with the intention to re-enter the well at a later date. TA have to statuses: with monitoring and without monitoring.

With monitoring: A well status where the well is abandoned, primary and secondary barriers are continuously monitored and routinely tested. There are no requirements for the duration of TA with monitoring [1].

Without monitoring:
A well status where the well is abandoned, primary and secondary barriers are <u>not</u> monitored and <u>not</u> routinely tested. The maximum duration of TA without monitoring shall be 3 years [1].

"Prior to Temporary Abandonment, the future for the well and planned duration for abandonment period shall be documented [1]."

2.1.3 Permanent abandonment

Permanent Abandonment is a well status, where the well is abandoned with the intent to not be used or re-entered again [1].

2.2 Cost of P&A

P&A is a huge investment with no return on investment (ROI). When a well is decommissioned it no longer yields profits for oil companies. As stated in "The Guideline of Well Abandonment Cost Estimation" by UK Oil and Gas, it has been estimated that the cost of PP&A in a mature area, such as the North Sea, would be £5-15 million (58-175 million NOK) on average per well the next 10 years [2]. There are as many as 6944 active wells on the NCS in 2021[3]. These wells will eventually need to be PP&A, which equates to £35- £104 billion (410-1200 billion NOK). This will be of great expense to oil companies, and therefore a focus over the past years have been to drive the cost of P&A down.

The main cost driver in P&A operation is time consumption. It is therefore important to start planning ahead to reduce time and increase efficiency. Innovation is also a crucial part in the pursuit to drive down cost. Companies in the industry invest huge amounts of funds to increase efficiency. In Norway the companies follow the standard NORSOK-D010. This Standard is created by the companies themselves in collaboration with the governing bodies. This collaboration between companies and governing bodies gives room for improvement and new discoveries in the industry, making the NCS an attractive area for investment.

P&A for an oil company is a liability and represents uncertainty with respect to future cost. This again will influence the stock value of the oil company. Having an efficient and robust P&A solution will have some positive effect on the stock value, thus it can also be said there are incentives to obtain some return on the investment – by means of increased stock value.

2.3 Plug & Abandonment Phases

P&A operations are commonly divided into different phases. In *"Guideline of Well Abandonment Cost Estimation"* UK Oil and Gas suggest dividing PP&A in three main phases; Phase 1: Reservoir Abandonment, Phase 2: Intermediate Abandonment and Phase 3: Wellhead and Conductor Removal. The UK phase definition have been adapted by Rushmore, which is a database collecting data from all participating oil companies and is often used for budgeting purposes and experience transfer. The Rushmore phase definition also include a Pre-Phase 1: Preparatory Work. [4][5]

The *"Guideline of Well Abandonment Cost Estimation"* by UK oil and Gas is only a suggestion, and operators on the NCS may choose to follow this guideline or define their own PP&A phases. NORSOK D-010 does not divide PP&A into phases.

Other operators, such as Repsol Norge AS, divide the P&A phases differently. Repsol phase 1 is equal to the Rushmore Pre-Phase 1. Repsol phase 2 is equal to Rushmore phase 1 and 2. Rushmore Phase 3 is equal to Repsol phase 3. The phases defined by Repsol are based on spread rates for each phase.

Ongoing P&A on GYDA, they have divided P&A into 3 phases [5]:

- Phase 1: Non-rig activity wireline (WL)
  This includes: installing barriers to enable removal of X-mas tree (XMT) and installation of drilling Blow Out Preventer (BOP)
- Phase 2: Rig Activity
  This includes: removal of completion and installation of reservoir and inflow-zone barriers and environmental plug
- Phase 3: Non-rig activity tubular cutting
  This includes: Preparatory work to cut all casings and conductors below seabed, that will later be removed by Pioneering Spirit (lifting vessel)

The following phase descriptions are based on the Rushmore definitions.

2.3.1 Pre-Phase 1: Preparatory work

Typical Pre-Phase 1 activities include [4][5]:

- Establishing access to wellbore
- Killing and removal of hydrocarbons

- Intervention operations
    - Removal of fish/fill
    - Through tubing logging
    - Well integrity activities
    - Removal of previously installed cement plugs

2.3.2 Phase 1: Containment of reservoir fluids

In Phase 1 the goal is isolate the reservoir by restoring the caprocks function with primary and secondary barriers with an eternal perspective. This includes all well types: production and injector wells. In Phase 1 the typical activities include [4][5]:

- Isolating the reservoir with cement plugs
- Verification of well barriers (logging/pressure testing)
- Fully or partly retrieving tubing, or leave in hole
- Removal of XMT

Note: Eternity is often defined as 500 years amongst operators on the NCS [5].

Phase 1 is completed when the permanent primary and secondary reservoir barriers are installed, and the reservoir is fully isolated from the surface.

2.3.3 Phase 2: Containment of formation fluids above the reservoir

The objective in phase 2 is to isolate any intermediate hydrocarbon or water-bearing permeable zones by setting additional barriers and finally installing a surface/environmental plug.
Typical activities in phase 2 include [4][5]:

- Setting cement plugs to contain formation fluids above the reservoir
- Setting environmental/surface plug
- Verification of well barriers (logging/pressure testing)
- Casing retrieval
- Casing milling
- Liner isolation

Phase 2 is complete when all hydrocarbon or water-bearing permeable zones have been isolated, i.e., no more plugging is required.

2.3.4 Phase 3: Details of wellhead and conductor removal

Phase 3 include [4][5]:

- Removal of wellhead
- Removal of conductor
- Removal of casing strings to below seabed
- Placement of cement to fill resulting craters

Phase 3 is completed when there is no further work needed to be done on the well.
This makes re-entry into the well almost impossible, given that well control system cannot be installed [6].

This demonstrates that P&A phases are defined differently amongst operators.

3 Well Barriers

On the NCS all oil and gas related activities are subject to Norwegian laws and regulations. The Norwegian Petroleum Safety Authority (PSA) is responsible to all petroleum related activities on the NCS and that the activities in the sector are pursued in a prudent manner [7]. The describe themselves as:

"The PSA is a government supervisory and administrative agency with regulatory responsibility for safety, the working environment, emergency preparedness and security in the petroleum sector." [7]

Figure 3.1 illustrates the regulatory hierarchy on the NCS.

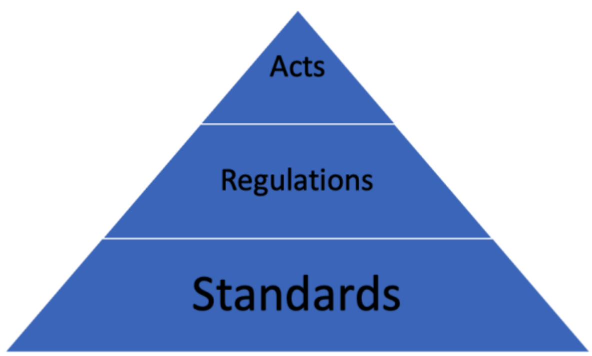


Figure 3.1 Regulatory Hierarchy on the NCS

In P&A, the Petroleum Activity Act §5-1 is of interest. It states that a decommissioning plan shall be presented at the earliest 5 years and the latest 2 years before the offshore installation is decommissioned [8]. This ensures good planning and that the P&A operations are performed efficiently and safely.

The facilities regulations Chapter VIII §48 is also of interest:

"Well Barriers shall be designed such that well integrity is ensured, and the barriers functions are safeguarded during the well's lifetime [9]."

On the NCS, the acts and regulations put forward by the PSA presents the requirements the companies are expected to achieve. It does not state how to complete these operations. This gives the companies more freedom to choose their own solutions. Cutting cost is of great interest to the companies regarding P&A. By giving the companies more freedom to choose, it generates investment in new technologies and methods in the pursuit of cutting costs as long as all of the given requirements are fulfilled.

In 1993 a collaborative initiative between the authorities and the petroleum industry initiated the development of the NORSOK standard. The ambitions of this initiative were to reduce project execution time, development and operating cost for petroleum installations on the NCS [1].

In the foreword of NORSOK D-010 page xi it states:
"The NORSOK standards shall [1]:

- *Bridge the gap based on experiences from the Norwegian continental shelf where the international standards are unsatisfactorily;*
- *Replace oil company specifications where possible;*
- *Be available as references for the authorities' regulations;*
- *Be cost effective; and*
- *Promote the Norwegian sector as an attractive area for investments and activities. "*

For the standards to contribute to the Norwegian petroleum industry being competitive both nationally and internationally, the development of new NORSOK standards and maintenance of existent standards is crucial. The NORSOK standard is currently, in 2021, on its revision 5.

The following is stated in [1]:
"The NORSOK standards are developed by experts from the Norwegian petroleum industry and approved according to the consensus principles as laid down by the guidelines given in NORSOK A-001N directive."

To achieve the main objectives of the NORSOK standard, companies often challenge the standard when new discoveries are made. By including companies in the Norwegian petroleum industry, the standard is updated to make the NCS an attractive area of investment. The new updates to the 5th revision include [1]:

- *"harmonization with the other North Sea countries' principles;*
- *updates principles and techniques for Plug and Abandonment;*
- *managed pressure drilling principles;*
- *alignment with relevant NORSOK and international standards."*

"Content have been deleted or moved to other location in the document, leaving the following clauses, figures and tables void to minimize changes in the document structure [1]:

- *clauses 4.7.5, 6.6.8 and 6.7.2*
- *Figures 27, 28 and 45*
- *Tables C.6, C.4 and C.56 (EAC tables in Annex C)"*

The changes to P&A principles and techniques are of special interest in this thesis. Some changes to the P&A principles include [1]:

- Tagging: tagging of internal cement plugs may be omitted under certain criteria
- Perforate, Wash and Cement (PWC) is defined in its own Element Acceptance Criteria (EAC) table
- Section Milling is defined in its own EAC table

3.1 Well Barrier Requirements

Well barriers are used to isolate any potential inflow-zones in the formation. This is done by combining WBEs with a different range of materials to get a cross-sectional well barrier. The requirements for which length, verification and material choice are all described in NORSOK D-010.

"The well barrier envelopes shall be defined prior to commencement of an activity by identifying all required well barrier elements (WBE) to be in place [1]."

There are four types of well barriers: Primary, Secondary, Crossflow and Environment Well barrier.

Primary Well Barrier

This is the first well barrier envelope that shall prevent any potential flow from inflow-zones/reservoir. This is the barrier in direct contact with the formation and shall be designed to withstand the pressures and stresses from the formation.

Secondary Well Barrier

This is the second well barrier envelope that shall prevent any potential flow from inflow-zones/reservoir should the primary well barrier fail.

Crossflow Well Barrier

A well barrier designed to stop undesired flow from one formation to another in the overburden.

Surface plug

Often referred to as an environmental plug. The purpose of an environmental plug is to isolate the open hole annuli, containing annuli fluid to prevent any contamination to the external environment.

In Chapter 5.2.3.2 in NORSOK D-010 it states [1]:

"The well barrier envelope shall consist of qualified WBEs, and be designed and constructed with the capability to:

- *a) Withstand the maximum differential pressure and temperature it can be exposed to (accounting for depletion or injection regimes in adjacent wells);*
- *b) Be leak tested, function tested or verified by other methods;*
- *c) Ensure no single failure of a well barrier or WBE can lead to uncontrolled release of formation fluid and well fluids throughout the lifecycle of the well;*
- *d) Re-establish a failed well barrier or establish another alternative well barrier;*
- *e) Operate competently and withstand the environment for which it can be exposed to for its intended service life;*

f) *Be independent of other well barrier envelopes and avoid having common WBEs to the extent possible."*

All of the points listed above are to ensure the health and safety of the workers and the environment.

3.1.1 Two barrier philosophy

The Facilities regulations §48 refers to NORSOK D-010 chapters 4, 5, 9 and 15 in order to fulfill the requirements regarding well barriers in the area of health, working environment and safety. NORSOK D-010 Chapter 5.2.3 describes well barrier requirements. *"The general principle is to operate with two defined well barrier envelopes against over-pressure and/or flow potential [1]."* The two well barrier philosophy is applied as independent barriers. If one barrier should fail, the other barrier shall not be affected by this event and prevent any unwanted release of well fluids to surface.

3.1.1.1 Number of barriers required:

The required number of barriers are generally considered to be two, as part of the two well barrier philosophy. The source of flow and the required number of well barrier are described in Chapter 5.2.3.1 *Minimum number of well barrier envelopes in well construction-, production/injection-phases and after permanent P&A* in NORSOK D-010.

Table 1 in NORSOK D-010 Chapter 5.2.3.1 states the following [1]:

Table 3.1 Minimum number of well barrier envelopes, taken directly from [1]

Pore-Pressure	**Source of inflow**	**Minimum number of well barrier envelopes**		
		Drilling, Completion & P&A Phase	**Production/ Injection/ Disposal Operations**	**After Permanent P&A**
Normal pressure Note that local over-pressured shallow hazards may occur in this interval	a) Interval with no hydrocarbon and no flow potential	One	Not relevant	Not relevant
	b) Interval with hydrocarbon and flow potential (included depleted reservoir)	Two	Two	Two
	c) Shallow water flow potential	Two	Two	One
Over pressure	d) Interval with no flow potential (with or without HC)	Two	One	One
	e) Interval with limited flow potential (with or without HC)	Two	Two	Two
	f) Interval with flow potential (including reservoir)	Two	Two	Two

The column of interest regarding PP&A is the *After Permanent P&A* column. The minimum number of required well barrier envelopes after PP&A is listed in the table above. In addition, under Table 1 on page 16 in NORSOK D-010 it lists 9 notes. Some noted are attached to points a, b, d and e.

Note 4 (point a) states that under a normal pressure interval with no hydrocarbon and no flow potential, *"an open hole to surface plug is required [1]"*.

Note 5 (point b) states: *"A pilot hole with confirmed shallow gas should be cemented back to surface [1]."*

Note 8 (points d and e) states:

"For overburden formations, with limited or no flow potential, the required number of barriers may be reduced by one providing a risk assessment demonstrates an acceptable risk level. The risk assessment shall cover all plausible load scenarios (including sustained casing pressure) and an account for operational limitations and uncertainties in fluid types, pore-pressure, barrier conditions etc [1]."

This means that in an over pressure interval with no potential flow, point d) in table 1, does not need a barrier envelope given the risk assessment covers the requirements stated in Note 8. In point e) it also means that the required number of barrier envelopes is reduced to one, given the risk assessment meets the requirements as stated in Note 8.

3.1.2 Well barrier schematics

Well Barrier Schematics (WBS) are used as an illustration of well barriers for all operations described in NORSOK D-010 chapter 5.2.2 [1]:

"Well Barrier Schematics (WBS) Shall be prepared for:

a) *All activities in the well; including all runs/assemblies;*
b) *When a new well component is acting as a WBE;*
c) *For illustrations of the completed well with XMT (planned and as built);*
d) *When changes to barrier envelopes are made in the production/injection phase;*
e) *For recompletion or workover on wells with deficient WBEs;*
f) *For status of temporarily abandoned wells; and*
g) *For final status of permanently abandoned wells."*

In NORSOK D-010 it states what information WBS should include. This means that the points listed what a WBS should include is a suggested possible choice deemed to be suitable without including or excluding other possible choices.

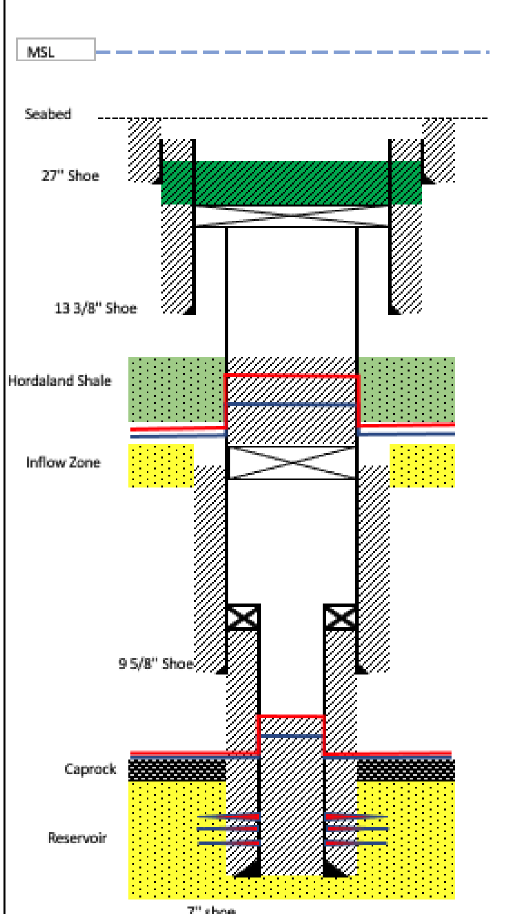
WBS is a useful tool in the planning phase of an operation. It illustrates e.g.:

- Well Barriers, with primary well barrier marked in blue and secondary barrier marked in red and surface plug marked in green.
- Reservoirs and sources of inflow

- Well information: field, well name, well type, “prepared by”, “Verified/Approved by” etc.
- Well integrity information

Figure 3.2 illustrates a WBS for an example well in final P&A status.

Well Barrier Diagram
Example Well



Final PP&A Schematic

Well Information		
Field	Example field	
Well no.:	1/1-A-1 A	
Well Type:	Oil Producer	
Validity:	Post Phase 3 PP&A	
Revision:	0	April 2021
Prepared:	Per Marius Staveland	
Well barrier elements	Verification of barrier elements	
PRIMARY RESERVOIR BARRIER		
	Well Barrier Element	Verification
1	Cement Plug	Tagged/dressed
2	7" Liner Cement	Logged
3	7" Liner	Pressure Test
4	In-situ formation	FIT/LOT
Well barrier elements	Verification of barrier elements	
SECONDARY RESERVOIR BARRIER		
	Well Barrier Element	Verification
1	Cement Plug	Tagged/dressed
2	7" Liner Cement	Logged
3	7" Liner	Pressure Test
4	In-situ formation	FIT/LOT
PRIMARY OVERBURDEN BARRIER		
	Well Barrier Element	Verification
1	Cement Plug	Tagged/dressed
2	9 5/8"1 Casing Bond/ Creeping Formation	Logged and Pressure Test
3	9 5/8" Casing	Pressure Test
4	In-situ formation	FIT/LOT
SECONDARY OVERBURDEN BARRIER		
1	Cement Plug	Tagged/dressed
2	9 5/8"1 Casing Bond/ Creeping Formation	Logged and Pressure Test
3	9 5/8" Casing	Pressure Test
4	In-situ formation	FIT/LOT
OPEN HOLE TO SURFACE BARRIER		
1	Cement Plug	Tagged/dressed
2	13 3/8" Casing Cement	Verified by pumped volume

Figure 3.2-WBS Example

In Figure 3.2, all well barriers are color coded. Under each of the barrier tables, there is a short description of verification method for each of the WBEs that form the well barrier envelope. This

WBS will later be used in an example well to describe the operational sequence, with extra focus on Phase 2 of PP&A.

3.1.3 Well barrier element requirements

A WBE is a physical element which by itself does not prevent any unwanted flow, but in combination with other WBEs forms a well barrier envelope [1]. To complete a well barrier envelope, it shall consist of qualified WBEs. The technical and operational requirements and guidelines are stated as the Element Acceptance Criteria (EAC) for which WBE it may concern. The EAC requirements has to be fulfilled in order for the WBE to be verified for its intended use. The EAC table consist of a number of points describing features, acceptance criteria and a column for information purposes. Table 3.2 shows an empty EAC for illustrative purposes.

Table 3.2-Element Acceptance Criteria, modified after [1]

Features	Acceptance Criteria	See
A. Description	Description of WBE	
B. Function	Description of Main function of WBE	
C. Design construction selection	1) Design criteria 2) Construction requirements	Name of specific references
D. Initial test and verification	Describes the method for verification of WBE, making it a part of a well barrier envelope	
E. Use	Use of the WBE to ensure its function is maintained	
F. Monitoring	Monitoring methodology	
G. Common well barrier	If element is a common WBE this describes additional criteria	

Table 3.2 describes how EAC tables are constructed. The testing and verification of WBEs is a critical part in ensuring that all intended properties of the WBEs are of acceptable quality. In table 26 on page 99 in NORSOK-D010 it states the requirements for a WBE to become part of a permanent well barrier. The material shall have the following properties [1]:

- Long term integrity
- Permeability lower than $5\mu D$ or equal to 1000 times the formation permeability whichever is greatest
- Chemical Stability
- Radial Shrinkage:
    - OH plugs/annular WBEs: low shrinkage
    - Internal, cased hole WBEs: long-term positive linear expansion
- Bond properly to tubulars
- A 40% safety factor to exposed mechanical loads
- Not have any detrimental effect on tubular integrity

The most commonly WBEs used in PP&A today is:

- Annulus Cement
- Casing
- Cement plug
- In-situ formation

In some well activities, the establishment of two independent well barriers is not possible or practical. A solution to this problem is to establish well barriers with a common WBE. In this scenario a risk analysis should be conducted to consider additional precautions as well as evaluating the EAC table for qualification and monitoring. If a well barrier has a common WBE, as shown in section G in table 3.2, additional acceptance criteria apply. *EAC table 24 – Cement plug* on page 211 in NORSOK D-010 provides an example. Figure 3.3 is an illustration of a common WBE. The same cement is used for primary and secondary barrier solution, i.e., same cement job.

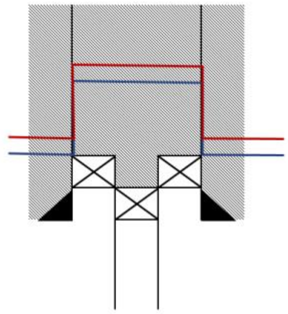


Figure 3.3-Common Well Barrier Element

3.1.4 Length requirement

3.1.4.1 Annulus Cement

On pages 205-207 in NORSOK D-010 the EAC table for Annulus cement is described. Under section B. Function it states: *"The purpose of the element is to provide a continuous, permanent seal along hole in the casing annulus or between casing strings, to prevent flow of formation fluids and/or injection fluids, resist pressures from above or below, and support casing or liner strings structurally [1]."* It is important to emphasize the wording in section B. Function, especially the word "continuous". This means that the length of acceptable bond quality of the annulus cement, must be verified as a continuous length as per the requirements stated in NORSOK D-010 rev. 5. Stacking intervals of appropriate bond quality is a solution that is yet to be included in the NORSOK D-010 rev. 5 and is a therefore a deviation from the standard. Stacking of external barriers will be highlighted later on in chapter 6 of this thesis.

In section C. Design, Construction and selection under point 7) planned annulus cement, the length recommendations are stated. Under point 7a) it also recommends that it should allow for future use of the well, e.g., sidetracks, recompletions and abandonments. Table 3.3 lists a modified version of points 7b-7g in EAC table 22 on page 205-206 in NORSOK D-010.

Table 3.3 Planned Cement Length, modified by [1]

Item type	**Planned Annulus Cement length**
General	Should be minimum 100 m MD above casing shoe/ window for kick tolerance and minimum 200 m MD if next section will penetrate a source of inflow
Conductor	Should be defined based on structural integrity
Surface Casing	Should be defined based on load conditions from well head equipment and operations. Top of cement should be at surface/seabed.
Intermediate Casing	If casing penetrates a source of inflow, the planned cement length should be minimum 200 m MD above the source of inflow
Production Casing/liner	Should be 200 m MD above planned production packer depth. If casing penetrates source of inflow, the planned cement length should be 200 m MD above the source of inflow
Shoe	A casing/liner should have a shoe track length of minimum 25 m MD

Table 3.3 *Planned Cement Length* is a recommendation for length of cement between casing annulus or between casing strings to achieve the required actual length of a qualified annulus cemented WBE.

When the annulus cement has been placed, it should be left undisturbed until sufficient strength is obtained to withstand the applied loads [1].

The requirements for annulus cement to be a qualified WBE are stated in NORSOK D-010 on pages 206-207 in EAC table 22 – Annulus Cement. In section D. Initial Verification, it states the requirements for what actual cement length for a qualified WBE shall be. The actual length requirements for an annulus cement WBE are listed in table 3.4, modified after EAC table 22 in NORSOK-D010.

Table 3.4 Actual cement length for Annulus, modified after [1]

Length Requirement	Verification Method
50 m MD	Displacement Calculations
30 m MD	Bond Logs
2x30 m MD if same annulus cement will be part of primary and secondary well barrier (common well barrier)	Bond Logs

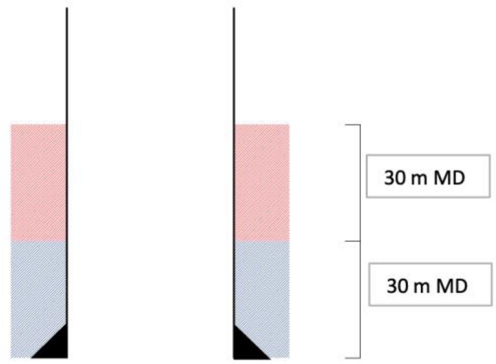


Figure 3.4 External WBE

Figure 3.4 illustrates an external WBE when the same annulus cement is used as a primary well barrier, marked in blue, and as a secondary barrier marked in red. As per the requirements, the qualified WBE actual length is 2x30m MD – and it must be verified by logging.

3.1.4.2 Cement Plug

A cement plug is an internal well barrier element. On pages 209-211, all of the requirements for a cement plug are listed in EAC Table 24- Cement plug. Under section C. Design, construction and selection. It is stated what the minimum cement plug length shall be:

Table 3.5 Minimum Cement Plug length, taken directly from [1]

Open hole cement plugs	Cased hole cement plugs	Open hole to surface plugs
100 m MD with minimum 50 m MD above any source of inflow/leakage point. A plug in transition from open hole to casing should extend at least 50 m MD above and below casing shoe	50 m MD if set on a mechanical/cement plug as fundament, otherwise 100 m MD If the qualified annular barrier length is 30 m and set on a mechanical/cement plug as fundament the plug may be 30 m.	50 m MD if set on a mechanical plug otherwise 100 m MD.

Point 10 in section C. Design, construction and selection is also an important part, as many cement plugs in PP&A is part of a cross-sectional barrier as per the requirements for a well barrier:

"If the cement plug is part of a cross-sectional barrier, it shall be positioned across the external WBE and its length shall match the requirement in the table above or the length of the external WBE, whichever is greatest [1]."

This states that a cement plug shall either meet the set requirements in table 3.5 or be the same length as the external WBE if the cement plug is part of a cross-sectional barrier, i.e., primary or secondary well barrier. A continuous cement plug in a cased hole is an acceptable solution as a part of the primary and secondary well barriers if the cement plug is placed on a verified foundation [1].

Figure 3.5 illustrates a cased hole cement plug, where the same cement is used as primary and secondary barriers.

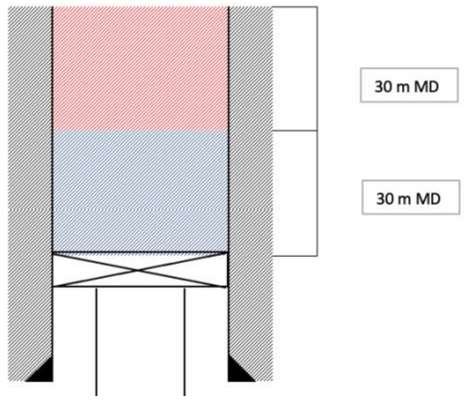


Figure 3.5 Cased Hole Cement Plug

In figure 3.5 the continuous cement plug is used as part of the primary well barrier, marked in blue, and as part of the secondary well barrier. As per the requirements the continuous cement plug is placed on a verified mechanical plug, and the length of the cement plug equals the length of the qualified annular barrier.

3.1.4.3 Creeping Formation

Creeping formation is an external barrier where the formation has crept to fill the void between the casing/liner and the bore hole wall. It is a relatively new discovered WBE compared to cement. The requirements for creeping formation are listed in NORSOK D-010 on pages 242-243 in EAC Table 52 – Creeping formation. In section B. Function it states: *"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 [1]."* As describe I chapter 3.1.4.1 Annulus cement, the important wording is "continuous". This means that the contact length shall be continuous and stacking of appropriate bond quality would be a deviation from the standard. The contact length requirements for creeping formation is stated below:

Table 3.6 Creeping formation length requirement, modified after [1]

Item Type	Length Requirement
Singular WBE with azimuthal qualified Bonding	30 m MD
WBE as part of the primary and secondary well barrier with azimuthal qualified Bonding	2x30 m MD

Previous requirement in NORSOK revision 4 was 50 m MD for creeping formation. [9]

Figure 3.6 is an illustration of creeping shale as an external barrier. The primary barrier is marked in blue, and the secondary barrier marked in red. The green shading illustrates green shale, e.g., Hordaland shale.

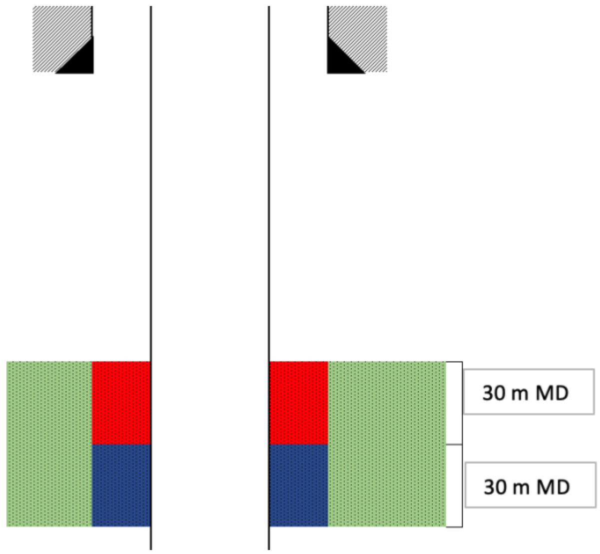


Figure 3.6 Creeping shale as external barrier

3.2 Barrier Verification

After placing WBE, it shall be verified in order to be qualified. The verification methods can be different for each of the WBEs and WBE material. To complete the primary and secondary well barrier envelope, all the WBEs shall be verified in order to qualify as a part of the well barrier envelope solution. When using cement as a barrier material, there are two possible WBE's: Annulus cement or cement plug. The verification method for these are different, given that there is no access to the wellbore once a cement plug is installed.

3.2.1 Testing of formation

On page 21 in NORSOK D-010 subchapter 5.2.3.6.7 *Testing of formation* it states: *"Rock mechanical data shall be systematically acquired in order to ensure well integrity in the drilling, production/injection, and abandonment phases [1]."* The most common formation tests are Formation integrity test (FIT), Leak-off test (LOT), and Extended leak-off test (XLOT).

3.2.1.1 Formation integrity test

In order to test the strength and integrity of a new formation, a FIT can be performed. After drilling out the shoe track and drilling some meters of new formation, the FIT is performed. Representative FIT results of the new formation can only be obtained if the previous cement job is of acceptable quality. The test is performed by pumping drilling fluid downhole at a constant rate in a closed well, to reach a pre-planned pressure. The FIT is a "test-to value" in order *"to confirm that the formation/annulus cement is capable of supporting a pre-defined pressure [1]."* Figure 3.7 is an illustration of how a FIT/LOT/XLOT is performed, and figure 3.8 represents a FIT graph.

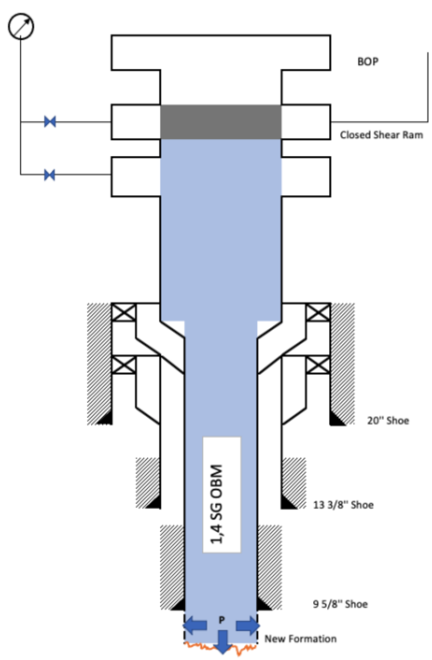


Figure 3.7 Illustration of FIT/LOT

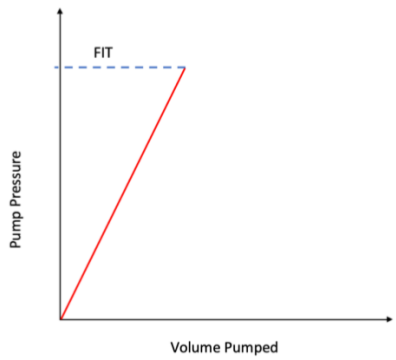


Figure 3.8 FIT Pressure vs. Volume

The information obtained by the FIT can be used to set casing depths, for well control options, obtain information about formation fracture pressures and drilling fluid design [11].

3.2.1.2 Leak-off test

When performing a LOT, the objective is *"to establish the pressure that the wellbore wall/annulus cement can support [1]"*, and the procedure is similar to a FIT. The wellbore is pressured up at a constant rate, and the pressure vs. volume pumped is plotted in a graph. When the graph deviates from a straight line, this is defined as the leak-off pressure (LOP). The LOP is defined when the formation breaks and starts taking fluids. Figure 3.7 illustrates how a LOT is performed and figure 3.9 illustrates a LOT graph.

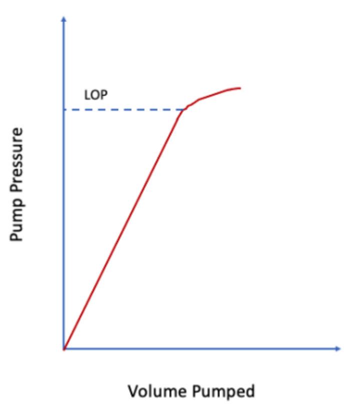


Figure 3.9 LOT Pressure vs. Volume

3.2.2 Annulus cement verification

In order to qualify annulus cement as part of the primary and/or secondary well barrier envelope, it needs to be verified. There are multiple testing methods for annulus cement, as stated on page 206 in NORSOK D-010 in section *D. Initial verification*:

"The cement length shall be verified by one of the following [1]":

a) Bonding logs
b) Displacement calculations
c) In addition to the above, a PIT/FIT or LOT shall be used to verify adequate formation/cement integrity

3.2.3 Cement plug

3.2.3.1 Tagging

Tagging is a verification method for cement plugs. This is done to ensure structural integrity of the cement plug. When tagging cement plugs, it is also common to dress (drill) on the plug to verify it has hardened. Figure 3.10 is an illustration of tagging.

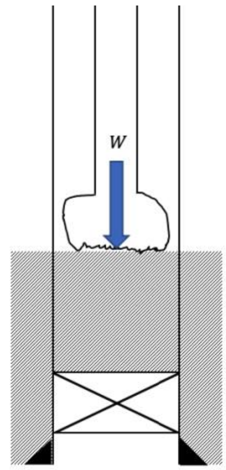


Figure 3.10 Tagging

In figure 3.10, W is applied load (weight) from the drillstring on the cement plug.

3.2.3.2 Initial verification

In order to qualify a cement plug as a WBE it needs to be verified. On page 211 initial verification process of the various plug types is described:

Table 3.7 Initial Verification of Cement Plugs, taken directly from [1]

Plug type	**Verification**
Open Hole Barrier	Tagging.
Cased Hole Barrier	Tagging. Pressure test, which shall: a) Be 70 bar (1000 psi) above estimated leak off pressure (LOT) below casing/potential leak path, or 35 bar (500 psi) for surface casing plugs; and b) Not exceed the casing pressure and the casing burst rating corrected for casing wear Test pressure may be reduced to 35 bars (500 psi) above LOT for mature fields where a large and relevant database exists with respect to expected LOT values If the Cement plug is set on a pressure tested foundation, a pressure test is not required. It shall be verified by tagging Tagging may be omitted if all the following condition are met: i. The cased hole cement plug has previously been verified by tagging for the same casing/borehole geometry, cement and fluid system, and ii. A successful and auditable track record has been established, using a qualification matrix with a documented parameter iii. The cement plug operation has been performed as per the criteria defined in the qualification matrix. In the event of losses, or the inability to perform the cased hole operation according to the parameter set defined in the qualification matrix, the cement plug shall be verified by tagging and pressure testing iv. The verification of the design and execution of the cement plug and the fulfilment of the qualification matrix criteria shall be documented and approved.
Open hole to surface plug	Tagging. Tagging may be omitted if the open hole to surface plug is set on a verified mechanical fundament.

The new updates to the standard allow for omitting tagging if certain criteria are met (ref table 3.7). It is also noteworthy that EAC table 24 – Cement plug does not apply to plugs installed using the PWC or section-milled method. These techniques have their own EAC tables and shall be referred to in these cases.

3.2.4 Creeping formation verifications

On pages 242-243, the requirements for initial test and verification are listed. Creeping formation as a WBE shall be verified, in accordance with NORSOK D-010, by [1]:

Table 3.8 Verification of Creeping formation

Item type	**Verification Method**
Position and length	Bond logs
Pressure Integrity	Application of a pressure differential across the interval. Should not be more than 30 m MD.
Formation Integrity at the base of the interval	Verified in accordance with Table 3 – Formation integrity requirements in NORSOK D-010 rev. 5 in order to qualify as a WBE

Under section D. Initial test and verification point 4) it states:
"*if the specific formation is preciously qualified by logging and FIT, logging is considered adequate for subsequent wells. Differential pressure testing is required if the log response is not conclusive or if there is uncertainty regarding geological similarity [1].*" This means that if logging and FIT have been done previously, e.g., when the well was initially drilled, logging alone is considered good enough given conclusive log data.

4 Barrier Materials

4.1 Cement

The prime material used for zonal isolation in PP&A is Portland cement. Portland cement is made by calcining a mixture of materials containing a high amounts $CaCO_3$, such as limestone, together with clay or shale at 2640°F. This technique results in partial fusion and “clinkers” are produced. Portland cement is obtained by combing clinkers and gypsum. This method was first discovered by Joseph Aspdin in 1824. After producing the material, it looked like Portland stone hence the name Portland cement. [6]

The reason for Portland cement being the primed material is because of accumulated knowledge over the years after J. Aspdin’s discovery. Portland cement is the most known and studied type of cementitious material. The cementing techniques and the material properties are widely understood. To obtain consistency in the cement properties standards have been developed for the production of cement. The class type of cement used as oil well cement is API class G being one of special hydraulic binding materials. *“API Class G: Intended for use as basic cement from surface to 8000 (ft) depth. It is manufactured in such a way that accelerators or retarders can be used to cover a wider range of well depths and temperatures. This class is available both as moderate and high sulfate-resistant types [6][12]”*

The benefits of API class G cement, as stated by Petro Drilling Mining Oil Co., are [13]:

“*Benefits:*

- *Thickening Times controllable with additives to enable placement to 550°F (287°C).*
- *Excellent Retarder Response for higher economic benefit in mix design.*
- *Low Free Fluids for cement integrity and durability.*
- *High Sulfate Resistance for high durability under harsh conditions.*
- *Non-Setting for uniformity in the column*
- *Consistent quality for slurry design portability”*

Cement is a very attractive barrier material choice for companies in the petroleum industry. Using cement as a WBE is attractive because of the following reasons:

- Available throughout the world
- Great knowledge and favorable:
    - Mixing techniques
    - Material properties
    - Placing techniques
- Cheap and efficient
- Adaptability with additives

4.2 Creeping Formation

As mentioned earlier, creeping formation is a relatively new discovery being used as a WBE in the industry today. This new type of external WBE can either form naturally or by activation. The most commonly rock type used for this is shale. Shale is a general term for argillaceous rocks, i.e., clay rich rocks. This type of barrier material being a formation, it comes with no material cost. This discovery can significantly reduce the total cost of P&A, removing the requirement for PWC or section milling [14].

It is also argued that creeping shale may be a better barrier material than cement, due to its permeability being extremely low. Reservoirs in the earth's crust have been sealed for millions of years with shale caprocks, thus giving shale as a barrier a proven track record. In addition, the typical permeability value for good, hardened class G Portland cement is 10-20 μD (microdarcy) [15]. This value may be higher due to downhole contamination. The cement has a permeability in the microdarcy range, while shale may have a permeability in the nanodarcy range [16]. Another problem that may occur using cement is micro-cracks/micro-annuli, which may cause integrity issues in the future. Ductile shale, however, will have self-healing behavior [17]. Typical values for creeping formation are listed in table 4.1, where data was obtained from [2][18]:

Table 4.1 Typical Permeability Values for Plugging Materials, Modified from [2]

Material	Permeability (μD, micro-Darcy)
Portland Cement (class G)	10
Shale	1-0,01

The main mechanism in creeping formation is creep, i.e., deformation. This is due to the mechanical properties of argillaceous rocks. Shale has a non-zero creep rate response due to inherent low strength and high ductility. Therefore, research have been conducted on how the creep mechanism works, what effects the creepage rate and if it is possible to activate the creep. The creep typically comes in 3 stages: primary/transient creep, secondary/steady state creep and tertiary/accelerating creep. Figure 4.1 illustrates a typical creep rate at the different stages. The figure is inspired by the graph from page 3 in [15].

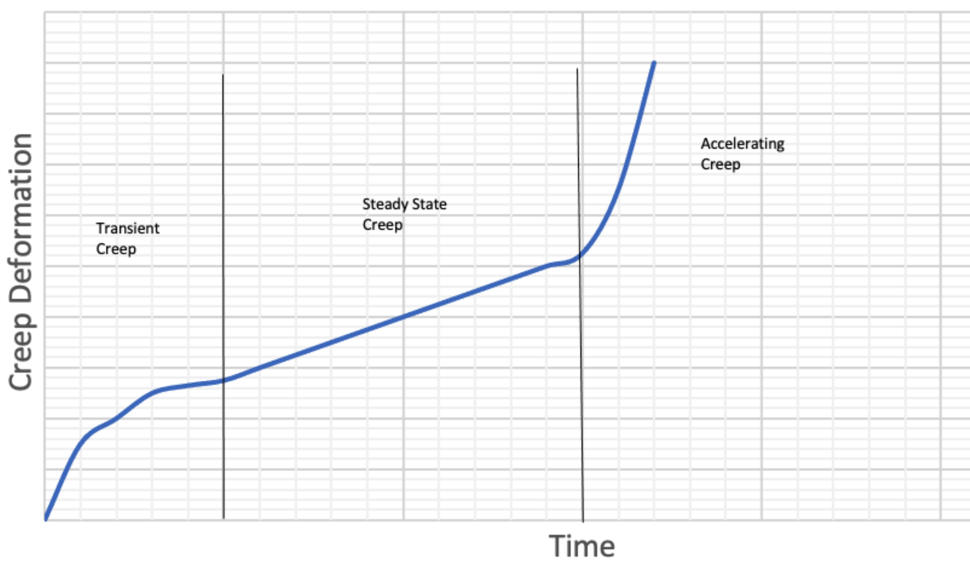


Figure 4.1 Creep Stages, Inspired by [15]

Figure 4.1 is only for illustrative purposes and does not reflect any data from either field or laboratory experiments.

After wellbore excavation, the transient creep starts occurring, then gradually transferring into steady state creep. In some cases, the steady state creep may result in tertiary creep, i.e., the deformation accelerates [15]. The most common creep is steady state. As shown in figure 4.1, the creep is time dependent. Stress is one parameter that increase creep in all rocks. Generally, it is assumed that creep is proportional with shear stresses in a material [15] [19].

The question then becomes: Has the formation crept enough to make a seal between formation and casing? Another challenge may be length of acceptable bond quality between casing and formation. As shown in figure 4.2 there has been intervals of acceptable bond quality, but the length of these intervals do not meet the requirements given in NORSOK D-010 rev. 5. Although not included in NORSOK D-010 rev.5 as a solution, stacking of these 2 intervals, i.e., cumulative length of acceptable bond quality, could result in meeting the required length. This would entail that the internal cement plug's length matches the length of the interval which in figure 4.2 is 70 m MD.

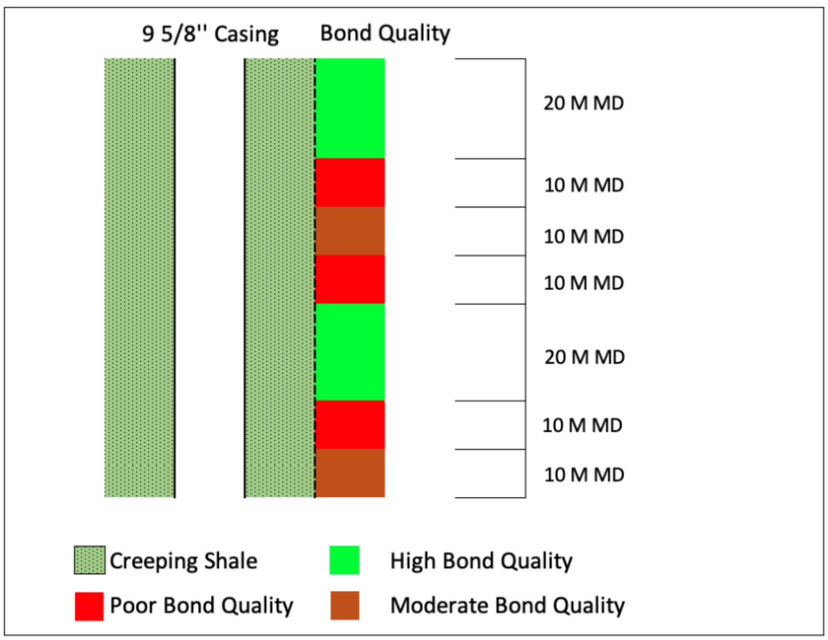


Figure 4.2 WBE with different Bond Quality

As NORSOK D-010 does not include the principle of stacking external barriers, this creates a challenge for using creeping formation as a WBE. Research has therefore been conducted to see if it is possible to activate/assist the creep rate. In paper [20] research was done to *"investigate if shale material will either form a pressure-tight barrier naturally by itself, or if it can be stimulated to form a barrier [20]."* The experiment was conducted in a laboratory. The parameters they used in each test were: vertical (axial) stress, horizontal stress, pore pressure, annular pressure, vertical effective stress, horizontal effective stress, differential effective stress and temperature. The experiments they conducted was a base test, NaOH test, elevated temperature test, sodium silicate test, and lithium silicate test. Their findings were that: *"annular pressure reduction, temperature increase, and annular fluid chemistry all have an effect on creep rate and barrier formation time [20]."*

In paper [21] analysis of logging data from 14 wells of the 9 5/8'' casing on the oil and gas field Varg was conducted. "*High-quality bonding is observed behind the 9 5/8-in. casing far above expected theoretical top of cement within single casing areas." [21]* This sparked an interest for understanding the mechanisms responsible for formation bonding development. Their observations are stated below in table 4.2:

Table 4.2 Observations from Varg, taken directly from [21]

Factor	Influence on Formation Bonding
Geological formations	Yes
Well age	Yes
Well Type	Yes
Drilling mud type	Unlikely
Duration of production	Yes
Volumes of production	Yes
Duration/volume of water/gas injection	Needs further investigation
Production/injection temperature	Likely
Well azimuth	Unlikely
Well deviation	Likely

With the information gained from the laboratory observations in [20] and field observation made in [21] one could state that known controllable parameters that effect creep rate are:

- Pressure
- Temperature
- Brine with additives (annular fluid chemistry)

5 Challenges and Remedies in P&A

In the discipline of P&A there are a number of different challenges which poses a threat to the operations. If the challenges are not dealt with it may cause an increase in project completion time and/or a threat to the integrity of the well. Health, Safety and Environment (HSE) is of first priority in every operation performed on the NCS. With each operation, comes increased risk. Reducing/combing operations would therefore not only reduce cost, but also reduce the risk associated with the operations.

5.1 Access to Wellbore

In order to install deep-set mechanical plugs to prepare the well for removal of XMT, a certain wellbore access is required. Access to wellbore can be challenging and costly. If the access is not checked, misruns can happen, and undesired time spent. Over the years of production, the casing strings are subjected to huge stresses, which may cause deformations (buckling and collapse) that hinder access. Scale, wax and asphaltene deposits in the tubing can also prevent wellbore access. Wellbore diagnostics is a valuable input for the planning of P&A to ensure the correct equipment is mobilized at any time and that the well budget is more reliable. Figure 5.1 illustrates scale build-up inside tubing.

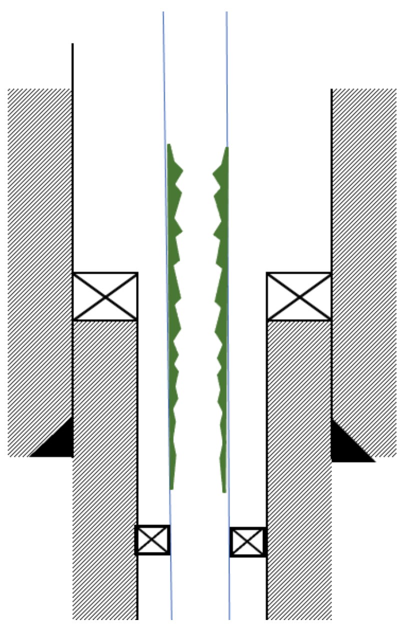


Figure 5.1 Scale build-up inside tubing

In order to remove the scale restriction, milling is often the only method. If the scale is $CaCO_3$, this can be removed by pumping acid downhole. Other scale types, e.g., barium scale must be removed mechanically by milling. This can be done by WL, coiled tubing, snubbing or drill pipe when in overbalance. [5]

Knowing this in advance is therefore important so that the correct equipment is available when the operation starts.

5.2 Logging through Two Tubulars

As of today, there are no reliable method for logging barrier quality cement between and behind two tubulars. It is very difficult to interpret the log results. Figure 5.2 illustrates a CBL in a liner lap.

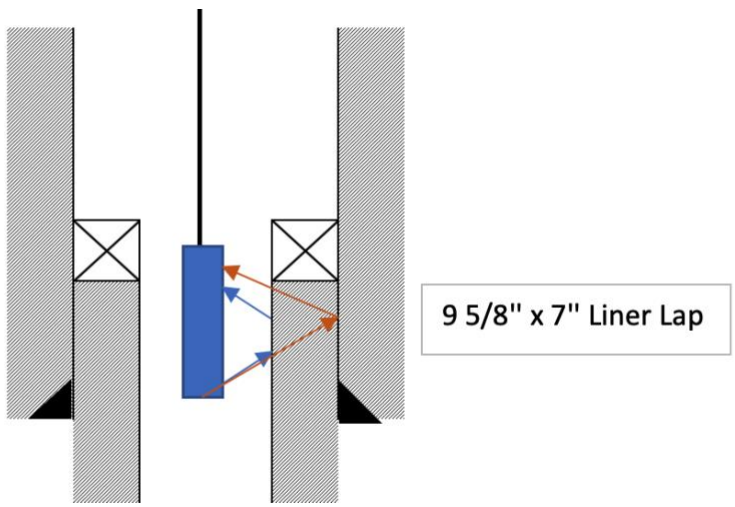


Figure 5.2 Logging in liner lap

A liner lap is rarely used as a WBE due to the challenge of interpreting logging data in a liner lap. It is possible to acquire interpretable logging data for the 9 5/8'' casing, but when a 7'' liner is cemented the data for the 7'' liner annulus cement becomes very difficult to interpret due to the signal interference of the outer casing. Difficult data interpretation of WBE leads to the WBE not being verified, thus not being able to utilize this as a WBE.

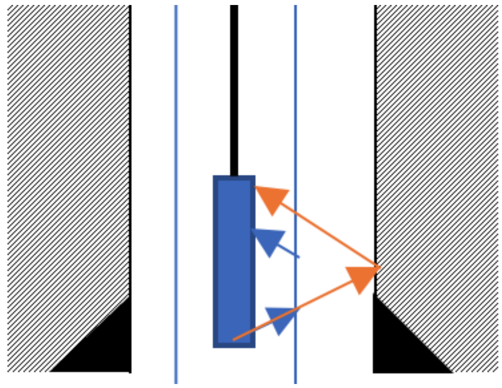


Figure 5.3 Logging through two tubulars

If a new technology that allows running logging tools inside the production tubing to log the cement bond quality of the casing outside, this could reduce the cost of P&A significantly [22]. This would allow for the tubing to be left in hole and reduce the requirement for heavy-duty and costly drilling rigs. Currently companies are developing such tools, e.g., Probe [22] and Wellguard [23].

With current available technology, the common practice is to cut and pull-out tubing in order to get access for logging tools to acquire data. This will also increase risk, time and cost of P&A and will require the use of heavy-duty drilling rigs.

5.3 Shrinkage of Cement

Another challenge in P&A is shrinkage of cement, this resulting in a micro-annulus. As stated in NORSOK D-010, one of the requirements for WBEs are that the material shall effectively be non-shrinking. A micro-annulus will increase the leakage rate of a cement plug/annulus cement, making the WBE a potential threat to well integrity. The solution to this problem is additives in the cement mixture that make the hardening process of cement non-shrinking.

5.4 Required Actual Length for Annular Barriers

Sometimes an annular barrier may not fulfill the required actual length. This might be because of poor cement job or insufficient formation bond quality. Figure 4.2 illustrates creeping shale as annular barrier where the contact length does not meet the continuous length requirement.

To rectify this, one would have to perforate, wash and cement (PWC) or perform section milling. This operation is time consuming and increases unwanted costs and risks. Another solution may be to make a deviation from the standard, though this requires a thorough risk analysis. In the industry it is suggested to implement the stacking technique. This would allow for stacking intervals of acceptable bond quality of external barriers in order to meet, or exceed, the required length of 30 m. This will be discussed more in chapter 6.3 Stacking.

5.5 Section Milling

Section milling is a remedy in P&A for wells with poor annulus cement or no access to the last open hole section. It is an operation which requires the use of heavy-duty costly rigs, is time consuming and is difficult to perform safely and efficiently. Section milling is in other words removal of casing by grinding away a portion of casing and cement. The hole needs to be kept clean by removal of the swarf and other produced debris. Swarf is a term used for metal fillings and/or shaving produced during milling operations. [2]

After the section milled window has been reached, a cement plug is placed. In revision 5 of NORSOK D-010, cement plug across a section milled interval is defined in its own EAC table: EAC table 60 in NORSOK D-010. On Page 254 the design, construction and selection criteria are listed [1]:

"The cement plug shall:

- *a) Be designed as per EAC table 24, paragraph C;*
- *b) Cover the section milled window and extend 50m into the casing."*

Under section C. 4 in EAC table 60 it also states that [1]:

"Placing a continuous cement plug in a section-milled window is an acceptable solution as part of the primary and secondary well barriers when placed on a verified foundation both in annulus and casing"

The verification methods listed for a cement plug across a section milled interval are:

- Tagging
- Pressure test with criteria listed in EAC table 60

5.6 Perforate, Wash and Cement

Perforate, Wash and Cement is a remedy in P&A, which is an alternative to section milling. It is required for wells with poor annulus cement or no access to last open hole section. The aim of the operation is to re-establish contact with annulus cement and formation in order to form a permanent well barrier [1]. As the name of the operation implies, the technique of PWC generally speaking is to perforate an interval of a casing, wash the annular space in this interval, and place cement internally and externally in the same interval

As with section milling, PWC cement plugs have a defined EAC table in revision 5 of NORSOK D-010. EAC table 61 – Perforate/wash/cement (PWC) cement plug is located at pages 256-257 in NORSOK D-010 rev. 5. Some key bullet points from Design, construction and selection are [1]:

2) *"Cement plug shall:*
    a. *Be designed as per EAC table 24 paragraph C*
    b. *Cover the perforations and the logged/verified interval in the annulus*
    c. *Extend 50 m MD above the perforation*
3) *Planned perforation interval length shall be sufficient to obtain, as a minimum, 30m MD of cement bonding, verified by logging, for the element to act as a single barrier. "*

The verification of annulus can be done by one of the following methods [1]:

- Bond logs
    - Actual cement length shall be minimum 30 m MD per barrier
- Qualification matrix with a documented parameter set
    - Losses, or inability to perform PWC in accordance with qualification matrix, the plug shall be drilled out and a CBL shall be performed
    - Minimum of 3 successful jobs, verified by drilling out and logging the cement behind the perforations, shall be completed prior to establishing a track record and a qualification matrix

"The internal cement plug shall be verified as per EAC table 24, paragraph D, and, if applicable, G [1]."

6 Discussion of Required Continuous Barrier Length

The required length of annular barriers in NORSOK is the same for creeping formation and annulus cement. The annular barrier length requirement does not take into account that the differential pressures and temperatures may be different depending on the formation and where the barriers are to be placed. In addition, different materials have different material properties, e.g., shale compared to cement. This chapter a discusses if it is possible to reduce the annular barrier length in a safe manner. Well barriers that do not meet the required length, as per NORSOK D-010, may in fact be good enough following a risk analysis and leakage calculations. The discussion will be based on Christer Sæth's Master's Thesis *A Risk Based Approach for Calculating Barrier length* at the University of Stavanger [24]. Christer's thesis was based on findings from SPE-177616.

A comparison of cement and shale as a barrier in the context of reduced barrier length will also be discussed. Another solution called stacking of barriers will also be presented, as the cumulative length of appropriate bond quality may not be an issue, but the continuous length is.

6.1 Reduced Annular Cement Length

Cement has a permeability, therefore flow through the material is possible. This means that annular cement barriers have a leakage rate, dependent on the differential pressure across it. In Christer Sæth's Master's thesis *A Risk Based Approach for Calculating Barrier length* he writes about the shallow zones of Valhall. The interval of the external cement is shorter than the required length given in NORSOK D-010. They constructed a risk-based approach for calculating barrier length. The argument used for shorter barrier length was by looking at leakage rates throughout the reservoir cement from a well complying to NORSOK D-010 requirements. This could then be used as a reference case when compared to other wells. A leakage calculation software based on Darcy's law called Simeo WellCem by Oxand was used. He used this software to set an Upper Accepted Case (UAC) for the leakage rate in a High-Pressure High Temperature well. Calculation of leakage rates from other wells or for barriers at shallower depths, can then be compared to the UAC. If the leakage rate of the planned design is lower than UAC, it could then be accepted in accordance with the risk-based approach. [24]

The argument of reduced external cement length is based on Darcy's law:

$$Q = \frac{kA}{\mu L} \times \Delta P$$

The three important parameters used in the argument is k (permeability), ΔP (differential pressure) and L (length of plug). By comparing Q to the UAC, the length L may be reduced given lower permeability or lower differential pressure.

6.2 Reduced Creeping Formation Length

In chapter 6.1 the argument of allowing for a reduce external cement barrier length is based on Darcy's law. The argument could also be used for creeping formation. Creeping formation being made of a different material than cement, will have different material properties. Accepting that cement and creeping formation is not impermeable and has a leakage rate, give grounds for comparing leakage rate to a UAC.

In the presentation *Why Shale Could be used as a Permanent Well Barrier Element* by BP, a comparison of leak rates between good cement and shale [17]:

«The Oil & Gas UK Guidelines for the suspension and abandonment of wells [Ref 2] require 30.5 m (100 ft) of good cement. Using a permeability value typical for good cement (20 microdarcy) and a pressure differential of 6.9 MN/m^2 (1,000 psi), a release rate of 0.25 m^3 of gas per year would be obtained for this length of barrier in a 7" casing, assuming the absence of cracks or micro-annuli." [17]

The calculation of leakage rate was then done for shale, with typical permeability, the same pressure differential, and same barrier dimensions. The leakage rate was found to be 0.0025 to 0.0000025 m^3 of gas per year. [17]

Comparing the two leakage rates indicate that only a few meters of shale will have a similar leakage rate to hundred meters of cement.

6.3 Stacking of Well Barrier Elements

Stacking of WBE's can be a solution to an external barrier that does not meet the required continuous length of acceptable bond quality. The idea is to add up intervals with acceptable bond quality in order to meet the total length requirement. Stacking WBE is commonly used in the industry today. A discussion point regarding stacking of WBE has been the minimum length of each interval that can be used when stacking these WBE's. The cumulative length of the internal cement plug must cover all the stacked external WBE's. [5]

Figure 6.1 is an illustration of 50 m qualified formation as barrier, where the log results vary. Creeping formation in this case was previously qualified as a barrier by differential pressure testing of the creeping formation with high bond quality. Here stacking can be used as a solution to achieve minimum 50 m of qualified barrier bond.

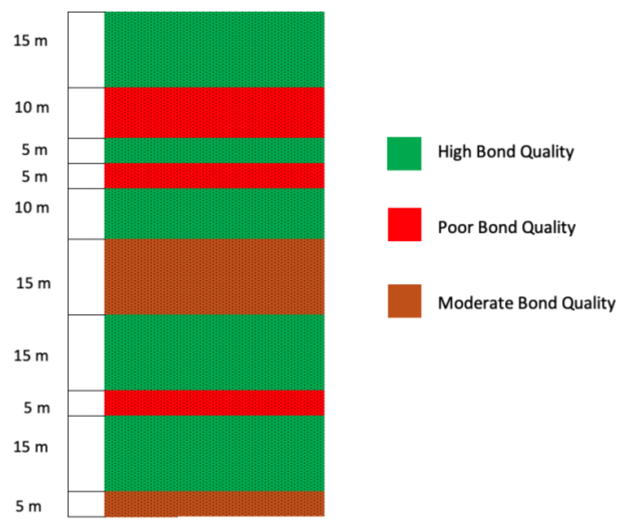


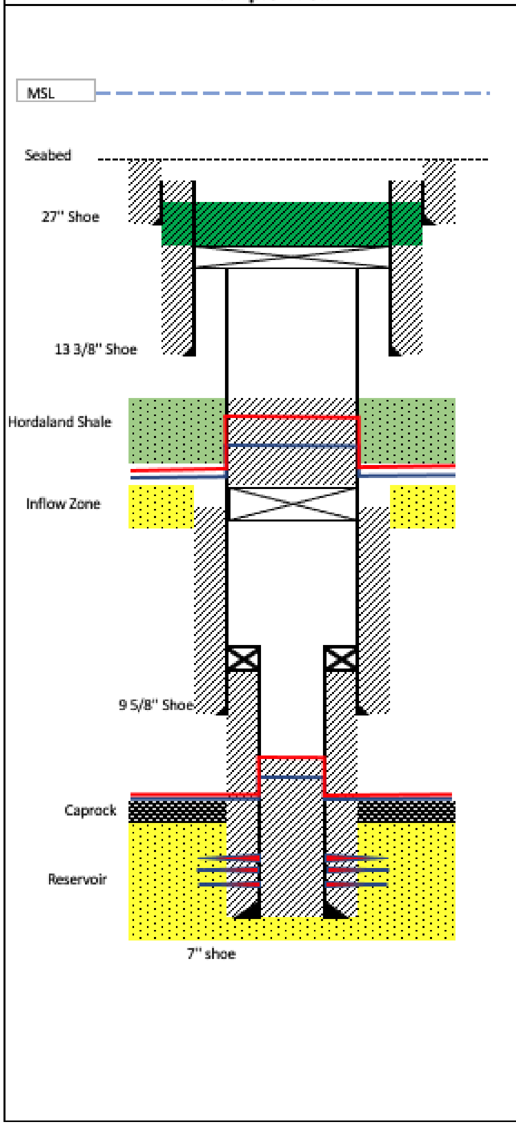
Figure 6.1 Variance of bond quality in Creeping formation

The argument used for stacking, similar to chapters 6.1 and 6.2, is based on Darcy's law. A cumulative length over an interval of acceptable bond quality can be considered as good, or even better, than a continuous length of acceptable bond quality of external barriers. This is due to the external barrier often having a longer length in a cumulative setting (i.e., lower leakage rate), compared to continuous setting.

7 Example Well with Shale as an External Barrier:

In this chapter an example well will be PP&A'ed. The WBS after phase 3 is illustrated in figure 7.1 and was constructed in Excel. The decommissioning plan for the well was made and submitted to the PSA 2 years prior to any of the PP&A operations commencing.

Well Barrier Diagram
Example Well



Final PP&A Schematic

Well Information		
Field	Example field	
Well no.:	1/1-A-1 A	
Well Type:	Oil Producer	
Validity:	Post Phase 3 PP&A	
Revision:	0	April 2021
Prepared:	Per Marius Staveland	
Well barrier elements	Verification of barrier elements	
PRIMARY RESERVOIR BARRIER		
	Well Barrier Element	Verification
1	Cement Plug	Tagged/dressed
2	7" Liner Cement	Logged
3	7" Liner	Pressure Test
4	In-situ formation	FIT/LOT
Well barrier elements	Verification of barrier elements	
SECONDARY RESERVOIR BARRIER		
	Well Barrier Element	Verification
1	Cement Plug	Tagged/dressed
2	7" Liner Cement	Logged
3	7" Liner	Pressure Test
4	In-situ formation	FIT/LOT
PRIMARY OVERBURDEN BARRIER		
	Well Barrier Element	Verification
1	Cement Plug	Tagged/dressed
2	9 5/8"1 Casing Bond/ Creeping Formation	Logged and Pressure Test
3	9 5/8" Casing	Pressure Test
4	In-situ formation	FIT/LOT
SECONDARY OVERBURDEN BARRIER		
1	Cement Plug	Tagged/dressed
2	9 5/8"1 Casing Bond/ Creeping Formation	Logged and Pressure Test
3	9 5/8" Casing	Pressure Test
4	In-situ formation	FIT/LOT
OPEN HOLE TO SURFACE BARRIER		
1	Cement Plug	Tagged/dressed
2	13 3/8" Casing Cement	Verified by pumped volume

Figure 7.1 Example Well After PP&A Phase 3

7.1 Introduction

The well is an old oil producer with gas lift and Annular Safety Valve (ASV) on a fixed installation offshore on the NCS. It was decided to start PP&A in the example field. After 30 years of production, the wells were no longer economically feasible to be in operation. 4 wells were previously plugged, in accordance with NORSOK D-010. A good track record of the qualification matrix for internal cement plug(s) has been established. This allows for omitting tagging internal cement in the future, as long as the qualification matrix parameters are satisfactory. By omitting tagging of internal cement, the plugging operations are reduced by several days per well. In addition, this also enabled installation of long internal cement plugs – improving robustness of the P&A [5]. Creeping formation has been tested in 3 wells and qualified for a 50 m interval with moderate to high bond quality and 95 bar pressure differential.

7.2 Operational Sequence

The P&A operations are divided into three (3) phases: Phase 1: Non-rig activity WL, Phase 2: Rig activity and Phase 3: Non-rig activity Tubular cutting. Phase 1 and phase 2 are performed as simultaneous operations. Phase 2 and phase 3 are also performed as simultaneous operations.

Note:

- The three (3) phases cannot be performed simultaneously

7.2.1 Phase 1: Non-rig activity WL

Wireline operations are performed from the BOP deck. The main outline procedure is as follow:

- Rig up WL pressure control equipment.
- Run in with debris collector to clean tubing and obstructions.
- Set deep plug on tractor. (highly deviated well)
- Punch and cut tubing above production packer.
- Circulate out potential HC from tubing and annulus. (returns to dedicated well)
- Run slickline wire brush and brush the ASV profile.
- Run in with bridge plug and set below ASV.
- Run in with tubing puncher tool and punch to release ASV.
- Pressure up against plug and release ASV

- Pull bridge plug from below ASV
- Set and test shallow plug (with pump open sub)
- Rig down pressure control equipment from well
- Nipple down and remove XMT. Prepare tubing hanger and wellhead
- Install running tool adapter in tubing hanger

7.2.2 Phase 2: Rig activity

Once the well has been secured with two (2) temporary well barriers, it is ready for the main drilling rig. The following outline procedure for this phase is as follows:

- Rig up High Pressure (HP) riser, BOP and Low Pressure (LP) riser and test same. Perform connection test
- Retrieve tubing hanger pack-off
- Run bond log in 9 5/8'' casing to verify external barriers
- Run in hole and set 9 5/8'' plug as mechanical foundation. Pressure test mechanical plug.
- Set 3x250 m cement plugs wet-in-wet, on top of mechanical plug (reservoir and Forties barriers)
- Cut and pull 9 5/8'' casing
- Set 13 3/8'' plug. Pressure test mechanical plug
- Set 100 m balanced cement plug on top of mechanical plug (environmental plug)
- Jet BOP
- Nipple down LP riser, diverter and BOP. Skid to next well.

7.2.3 Phase 3: Non-rig activity (tubular cutting)

Phase 3 activity is performed simultaneously with phase 2 rig activities. The cutting operation is operated from the BOP deck and the verification lifting operations take place at the cellar deck. The tubulars will be cut and be prepared for lifting by a lifting vessel. The main outline operations are as follows:

- Perform deep cut (2 m below seabed) through 13 3/8'' and 20'' casings - abrasive cut
- Verify cut by lifting 20 cm using special built hydraulic jacking frame.
- Perform shallow cut (11 m below WH) through 13 3/8'' and 20'' casings – abrasive cut
- Verify cut by lifting and visual inspection

- Install securing pin inside casing, across upper cut

Note:

- The upper 11 m will be removed together with platform topsides module (lifting vessel)
- Conductors and casings will be lifted out in batches of 4 by lifting vessel
    - The conductor and casing will be connected through a drill and pin operation to make it possible to remove these two stings simultaneously

7.3 Deviation from the NORSOK D-010 revision 5

The execution of the PP&A included some deviations from the NORSOK D-010 standard. Log results showed that the annulus barriers behind the 9 5/8'' casing, creeping formation, did not meet the required continuous contact length. Figure 7.2 shows the bond quality of the annulus barrier:

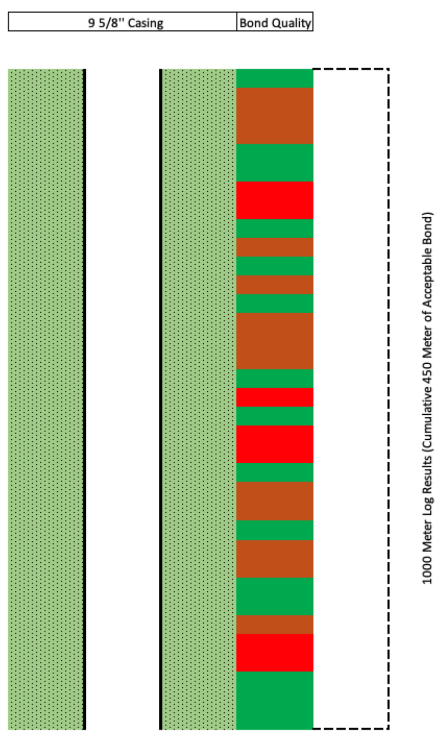


Figure 7.2 Log Results

PWC here is no option, since the formation bond to the casing is too high and the washing procedure would be ineffective. One option would be to section mill the interval. This increases risk, time and cost. It was decided to perform a deviation internally to avoid section milling. The solution of stacking of the qualified interval of 2x50 m of creeping formation was used. As shown in the procedure in 7.2.2 Phase 2: Rig Activity, the internal cement plug was set as a 3x250 m continuous plug. Logging results showed a total of 450 m cumulative length of qualified creeping formation (mod to high bond or better), but was unable to identify two 50 m continuous intervals. (50 m is the length that has been qualified) Qualified creeping formation with lengths shorter than 4 m was not included in the cumulative length of 450 m. The use of stacking allows for verification of barriers over an interval, i.e., cumulative length of acceptable bond quality. This would remove the need for PWC and section milling – reducing risk, cost and time. One of the main risks removed is associated with swarf potentially compromising the BOP.

Stacking of WBE also increases the robustness of the barrier envelope as discussed in chapter 6.3.

8 Conclusion

The NORSOK standard requirements are based on historical practices and presents generalized requirements for WBE's. Different materials have different properties, which may be better or worse for use as WBE's. The length requirements do not take into account where the barrier is set, differential pressure it will be exposed to, or material properties. Some of the updates to NORSOK D-010 rev. 5 increases efficiency, e.g., allow omitting tagging of cement plugs given a documented and an auditable track record of a qualification matrix. This allows for installation of long internal cement plugs – increasing the robustness of the P&A. However, some principles were not updated and remain unchanged in the new revision (rev. 5). Stacking of WBE's, especially regarding creeping formation, may in fact increase the robustness of the P&A.

Creeping formation is a relatively new well barrier material. The material comes with no material cost and has a proven record of sealing reservoir for millions of years. In addition, the material properties are favorable for the use as a WBE. It has a much lower permeability than conventional class G cement, drastically reducing the leakage rate. As shown in the presentation given by BP, a few meters of shale will have the same sealing capability as 100 m of cement [17]. In contrast with cement, a high strength material, shale is ductile and will have self-healing behavior [17]. The mechanism for shale to creep can happen naturally or by activation/assistance. It removes the need for PWC and section milling – reducing risk, cost and time.

The length requirements for creeping formation and annulus cement are the same in NORSOK D-010. This is due to creeping formation being a relatively new well barrier material. In revision 4 the length requirement for creeping formation was larger than annulus cement, 50 m vs. 30 m respectively, but given new discoveries it has been reduced to 30 m per barrier element. This gives grounds for a discussion around required contact length for creeping formation as a barrier. Creeping shale as a barrier requires qualification by testing, but cement does not, given sufficient bond quality.

In some EAC tables, e.g., EAC table 22, it states that the purpose of the element is to provide a continuous, permanent seal. The length shall be verified by bond logs, but it does not state that the length of acceptable bond quality shall be continuous. The confusion here is: is it only the cement plug that need to be continuous or does the length of verified bond quality also have to be continuous? This has then sparked a debate in the industry on “continuous” versus “cumulative”. Stacking well barriers reduces risk, cost and time as it removes the need for PWC or section milling. Allowing the use of stacking is previously argued by using Darcy’s law. When stacking of barriers occur, the interval length of stacked barriers is greater than a conventional 2x30 m as per the NORSOK D-010 standard. The gives grounds to allow stacking of external barriers.

Stacking is already in use today, but it is a deviation from NORSOK D-010 rev. 5. It has been suggested that more testing should be performed to confirm that stacking of WBE can be used. Based on the arguments above, testing should not be required.

Another question that may have an impact on required length for WBEs are: What will happen to creeping shale vs annulus cement in the next 500 years? Given that cement is a high-strength, low ductile material, will micro-cracks/micro-annuli start to form in the annulus cement compromising well integrity? However, formation is likely to continue creeping and creating more meters of bond with barrier quality.

9 References

[1]: Standards Norway, *Well integrity in drilling and well operations*, NORSOK Standard D-010 Rev. 5, 2021

[2]: Bakker, S., Vrålstad, T., and Tomasgard, A., 2019. An optimization model for the planning of offshore plug and abandonment campaigns. *Journal of Petroleum Science and Engineering*, [online] 180, pp.369-379. Available at: <https://www.sciencedirect.com/science/article/pii/S0920410519304966#bib25> [Accessed 5 February 2021].

[3]: Factpages.npd.no. 2021. *Faktasider - OD*. [online] Available at: <https://factpages.npd.no/no/wellbore/Statistics/EntryYear> [Accessed 26 February 2021].

[4]: IHS Markit. 2021. *IHS Markit Rushmore Abandonment Performance Review (APR)*. [online] Available at: <https://ihsmarkit.com/products/abandonments-performance-review.html> [Accessed 6 May 2021].

[5]: Personal conversations with Per Ove Staveland, Senior P&A Engineer Repsol Norge AS, 2020-2021

[6]: Khalifeh, M., and Saasen, A., 2021. *Introduction to Permanent Plug and Abandonment of Wells*. [ebook] Springer, Cham. Available at: <https://library.oapen.org/viewer/web/viewer.html?file=/bitstream/handle/20.500.12657/23318/1006837.pdf?sequence=1&isAllowed=y> [Accessed 22 February 2021].

[7]: Ptil.no. 2021. *Role and area of responsibility*. [online] Available at: <https://www.ptil.no/en/about-us/role-and-area-of-responsibility/> [Accessed 5 April 2021].

[8]: Lovdata.no. 2021. *Lov om petroleumsvirksomhet [petroleumsloven] - Lovdata*. [online] Available at: <https://lovdata.no/dokument/NL/lov/1996-11-29-72> [Accessed 5 April 2021].

[9]: Ptil.no. 2021. *Brønnbarrierer*. [online] Available at: <https://www.ptil.no/regelverk/alle-forskrifter/innretningsforskriften/VIII/48/?expandGuideline=true&hideParagraph=true> [Accessed 5 April 2021].

[10]: Standards Norway, *Well integrity in drilling and well operations,* NORSOK Standard D-010 Rev. 4, 2013

[11]: PetroWiki. 2021. *Formation integrity test - PetroWiki*. [online] Available at: <https://petrowiki.spe.org/Formation_integrity_test> [Accessed 26 April 2021].

[12]: American Petroleum Institute. Production Dept. 1988. *API specification 10A—Specificationfor materials and testing for well cements*, in Section 2. American Petroleum Institute.

[13]: Petrodmo.com. 2021. *Oil Well Cement Class G*. [online] Available at: <https://www.petrodmo.com/products/oil-well-cement-class-g> [Accessed 6 May 2021].

[14]: van Oort, E., and et al, 2020, *Simplifying Well Abandonments Using Shale as a Barrier*, IADC/SPE-199654-MS, Presented at IADC/SPE International Drilling Conference and Exhibition in Galveston, Texas, 3-5 March 2020

[15]: Kristiansen, T.G., and et al, 2018, *Activation Shale from Well Barriers: Theory and Field Examples*, SPE-191607-MS, presented at 2018 SPE Annual Technical Conference and Exhibition Held in Dallas, Texas, 24-26 September 2018.

[16]: Kristiansen, T.G., and et al, 2021, *Implementing a Strategy for Shale as Well Barrier in New Wells*, SPE/IADC-204075-MS, was due to be presented at the SPE/IADC International Drilling Conference and Exhibition to be held virtually on 8-12 March 2021.

[17]: Kristiansen, T.G., 2015, *Why Shale Could be used as a Permanent Well Barrier Element*, Presentation: BP P&A forum 29 Octorber 2015, Stavanger

[18]: Warren, J.K. 2006. Evaporites: sediments, resources and hydrocarbons. Heidelberg: Springer.978-3-540-26011-0.

[19]: Fjær, E., Holt, R.M., Horsrud, P., Raaen, A.M., and Risnes, R., : *Petroleum Related Rock Mechanics*, Elsevier, 2008

[20]: Thombare, A., Aldin, M., van Oort, E., 2020, *Experimental Technique to investigate Shale Creep for Annular Barrier Formation in Oil and Gas Wells*, ARMA 20-2073, Presented at US Rock Mechanics/Geomechanics Symposium in Golden, Colorado, USA, 28. June-1. July 2020

[21]: Noble, L., and et al, 2019, *Study of Formation Bonding in the Wells of the Varg Field Based on Ultrasonic and Sonic Wireline Log Data*, SPE/IADC-194172-MS, presented at the SPRE/IADC Drilling International Conference and Exhibition held in The Hague, The Netherlands, 5-7 March 2019.

[22]: Zhang, J., and et al, 2019, *Multi-String Isolation Logging – A Cost Effective Solution for P&A*, SPE-195607-MS, presented at SPE Norway One Day Seminar held in Bergen, Norway, 14 May 2019.

[23]: Wellguard.no. 2021. *WellGuardAS*. [online] Available at: <https://www.wellguard.no/logging> [Accessed 13 May 2021].

[24]: Sæth, C.A., 2018, *A Risk Based Approach for Calculating Barrier Lengths*, Master Thesis, University of Stavanger