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Qualification of the Cementitious Material Rock-based Geopolymer in Permanent Plug & Abandonment

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University of Stavanger
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Abstract

When an oil & gas well proves not to be economically favourable anymore, or is technically inviable, the well has served its life and are due to be shut-down and sealed, also referred to as permanent plug & abandonment. Depending on the country one operates in, different local regulatory requirements have to be followed. Various guidelines, set by the regulatory authorities, refer to recognized industry standards. Within permanent plug & abandonment, four recognized industry standards concerning well integrity and barriers are covered; NORSOK D-010 well integrity in drilling and well operations, Oil & Gas United Kingdom well decommissioning guidelines, API wellbore plugging and abandonment and DNV risk based abandonment of wells.

Portland cements are the most common used barrier material in today's permanent plug & abandonment operations. The use of Portland cements have faced excessive well integrity problems since it was first introduced, where common issues has been development of micro-annuli over time due to shrinkage, mechanical failure, and degradation at elevated temperatures. Use of Portland cement has historically been inexpensive and further satisfying fundamental barrier material requirements, despite its weaknesses. The oil & gas industry has researched substitutes in the last decade, but few alternatives have had commercial success.

Through a technical qualification process based on review and comparison of industry accepted standards, the rock-based geopolymer cement is proved to be acceptable as a barrier material in the oil & gas industry. Geopolymers naturally expanding properties together with a permeability similar to shale is advantageous to seal the wellbore against leakage to the external environment. Combined with an environmental footprint that is less than half of Portland cements, geopolymer-based cement shows many benefits compared to Portland cement and can thus be a viable barrier substitution material.

Nomenclature

Abbreviations

ALARP	As Low as Reasonably Possible
API	American Petroleum Institute
BFS	Blast Furnace Slag
BOP	Blow Out Preventer
°C	Degree Celsius
CBL	Cement Bond Log
CO2	Carbon dioxide
CST	Cement Support Tool
DHSV	Downhole Safety Valve
DNV	Det Norske Veritas
D-010	Drilling 010
D&W	Drilling & Wells
EAC	Element Acceptance Criteria
ECD	Equivalent Circulating Density
E&P	Exploration & Development
FEA	Finite Element Analysis
FIT	Formation Integrity Test
ft	Feet
HSE	Health, Safety, and Environment
HPHT	High Pressure, High Temperature
LOP	Leak-off Pressure
LOT	Leak-off Test
MD	Measured Depth
MT	Metric Tonne
NCS	Norwegian Continental Shelf
NORSOK	NORsk SOkkels Konkurranseposisjon
N/A	Not Available
OBM	Oil-based Mud
OGUK	Oil & Gas United Kingdom
OH	Open Hole
UKOOA	United Kingdom Offshore Operators Association
USIT	UltraSonic Imager Tool
OPC	Ordinary Portland Cement
PP&A	Permanent Plug & Abandonment

PSA	Petroleum Safety Authorities
PWC	Perf, Wash & Cement
P&A	Plug & Abandonment
QA/QC	Quality Assurance, Quality Control
Rev.	Revision
RP	Recommended Practice
R&D	Research & Development
SDP	Section Design Pressure
THC	Total Hydrocarbon Content
TOC	Top of Cement
WBE	Well Barrier Element
WBM	Water-based Mud
WDP	Well Design Pressure
WOC	Waiting on Cement
XLOT	Extended Leak-off Test

Chemical Abbreviations

H	Hydrogen	atomic number 1
C	Carbon	atomic number 6
O	Oxygen	atomic number 8
Al	Aluminium	atomic number 13
Si	Silicon	atomic number 14
S	Sulfur	atomic number 16
Ca	Calcium	atomic number 20

Mathematical Abbreviations

F_{fc}	Filter cake's friction force
kg/m^3	Kilogram per cubic metre
N_f	Fatigue life cycles
Nm^{-2}	Newton per square meter
mD	Milli Darcy (10^{-3} Darcy)
MJ	Mega Joule $\left(\frac{kg \times m^2}{s^2}\right)$
MT	Metric Tonne (10^3kg)
m^2s^{-1}	Square Meter per Second
Pa	Pascal $\left(\frac{N}{m^2}\right)$
Psi	Pound-force per square inch $\left(\frac{lb_f}{in^2}\right)$
Wt.%	Percent of weight
%	Percent
ΔP_{f2}	Delta pressure induced from spacer fluid

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1. Introduction

1.1. Background

In the oil and gas industry, each field asset can be divided into four developing segments: exploration, development, production, and decommissioning. This thesis will focus on the last segment, decommissioning, specifically well decommissioning, as illustrated in Figure 1.1. This involves performing plug & abandonment (P&A) activities where the purpose is to permanently abandon the well bore(s) when they are not able to produce economically favourable volumes of gas and/or oil or are technically inviable.

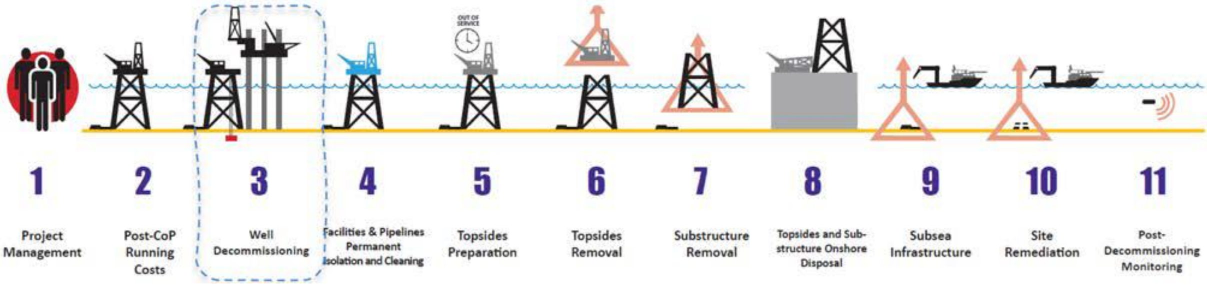


Figure 1.1: Example of Stages in the Decommissioning Process (Rios R. and Ars F. 2020, figure 1)

The P&A-part in decommissioning is well-known in the industry as time consuming and cost intensive. In the decommissioning phase, the operator does not see cash flow opportunities in the future and one of the main objectives is to safely abandon the well(s) with as low cost as possible.

Several new technologies have entered the market in the last couple of decades in the P&A-segment, such as dual string section milling (Abrado, Weatherford, Wellbore Integrity Solutions), thermal activated resin to remediate leaks for P&A (WellCem), perforate & test annulus well integrity (Archer, HydraWell), perforate, wash & cement (PWC; Archer, HydraWell, Well Integrity Solutions), casing expansion tool to expand casings to close micro annulus or cement fractures (HydraWell, Well Integrity Solutions, WinterHawk, W. T. Bell), thermite (Interwell) and open hole high expansion packers & plugs (Baker Hughes, BiSN, TAM International). There are also technologies under research & development (R&D) that has potential savings with regards to cost and environment.

In addition to developing smarter, less cost intensive solutions for the industry, there has also been a focus towards creating more sustainable solutions mainly driven by the comprehensive political debates and climate-change dialogues around the world (Sokal S. 2020, p. 1).

Companies and countries are under extreme pressure to find more environmentally friendly and sustainable products in the exploration & production (E&P)-business segment. CO_2 injection is one example while another is the cementitious material in P&A.

1.2. Problem Description

Achieving a cross-sectional barrier in the vertical and horizontal seal direction, is crucial in permanent plug & abandonment (PP&A) and is one of the requirements in NORsk SOkkels Konkurranseposisjon (NORSOK) D-010 and equivalent standards such as Oil & Gas UK (OGUK). NORSOK D-010 (2021, p. 97) says, "permanent well barriers shall extend across the full cross section of the well, include all annuli and seal both vertically and horizontally", ref. Figure 1.2.

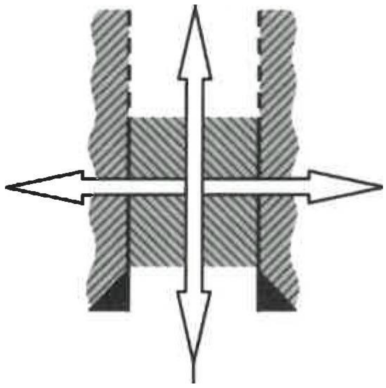


Figure 1.2: Vertical and Horizontal Seal Directions (NORSOK D-010 rev. 5, figure 40)

The most common conventional barrier material for PP&A and in general all cementing applications used in the E&P-industry today is Portland cement (Rios R. and Ars F. 2021, pp. 3-4). Some of the advantages with the use of Portland cement is that it satisfies the fundamental criteria, which is being comparable with the in-situ cap rock. Use of cement is also inexpensive as a material, in addition to have low bulk permeability and being highly durable when a sufficient length is accomplished, i.e., having good barrier properties.

Use of Ordinary Portland Cement (OPC), also referred to as just Portland cement, for cementing downhole has faced wellbore integrity issues over time (Salehi S. et al. 2017, pp. 1-2). In the recent years there has been advancement in the additives in Portland cement, making it more robust in different environments such as gaseous, shallow depths, and high pressure & high temperature (HPHT). Some of the problems faced with the use of Portland cement has been micro-annuli leakage, mechanical failure, shrinkage, chemical attacks, sustained casing pressure and durability issues. The cement type suffers a reduction in compressional strength over time when exposed to downhole conditions with high temperature and pressure.

According to Abdullah MMAB. (2011, pp. 247-248), there has been little to no changes in the past decades in the cementitious material used as a wellbore barrier despite several research articles and papers has been published on the use of geopolymer-based cement. Geopolymer cement is inorganic matter made by a reaction between the amorphous materials aluminate and silicate, which is a vital step to environmentally friendly production of cement. It is important to note that geopolymer cement is made independently of Portland cement and thus represent a complete substitution of the carbonization process.

Fly ash is a natural waste material in combustion processes and abundantly available worldwide but the usage of it is limited (Abdullah MMAB 2011, p. 248). This by-product is a base material in specific types of geopolymer cements. Fly ash is an important additive in geopolymer cements since it is Silicon (Si) rich and normally contains from 40 to 60 percent of it depending on the mineral composition of the origin material. By using fly ash in concrete, it is documented an increase in durability and life cycle expectancy. Utilizing a waste material from other industries, the overall CO_2-emissions from producing fly ash-based Geopolymer cement is further decreased, giving a positive impact on the environment in addition to saving cost.

1.3. Objectives of Research

Geopolymer cement is introduced as a substitute barrier material to ordinary Portland cement. The main purpose behind undertaking a verification process for use of geopolymer-based cement in cementing operations in the oil & gas industry is the environmental impact. Such change can cause and create the need for technological change in P&A barrier material. A study made in 2002 found that production of Portland cement yields six times more CO2-emissions than geopolymer cement (Chok MF. 2002, p. 1).

The objective of this thesis is to substantiate the use of geopolymer cement through detailed review of regulatory and institutional standards and have a novel approach to deciding whether the use of geopolymer cement is acceptable or not. OGUK Well Decommissioning Guidelines (2018), American Petroleum Institute (API) Wellbore Permanent Abandonment (2021), and Det Norske Veritas (DNV) Risk based Abandonment of Wells (2020) will be compared with the latest version of NORSOK D-010 Well Integrity in Drilling and Well Operations (2021, rev. 5). A comparison of the technology qualification standards from OGUK Guidelines on Qualification of Materials for the Abandonment of Wells (2015) and DNV Technology Qualification (2019) will be reviewed and discussed. Literature from the presented standards will focus on requirements of PP&A materials and technology qualification and, a detailed description of barrier requirements to ultimately demonstrate that geopolymer-based cement is as good as Portland cement barrier wise.

Experiences and learnings gathered from the field and laboratory tests performed up to end of 2021 will be shared and discussed. Furthermore, it will be assessed whether a separate Element Acceptance Criteria (EAC) table, similar to NORSOK D-010, will be created and presented specifically for a geopolymer plug. See example in Table 1.1.

Table 1.1: Example of an EAC table Description (Standard Norge 2021, table 5)

Features	Acceptance criteria	See
A. Description	This is a description of the WBE.	
B. Function	This describes the main function of the WBE.	
C. Design (capacity, rating, and function), construction and selection	For WBEs that are constructed in the field (e.g., drilling fluid, cement), this should describe a) design criteria, such as maximal load conditions that the WBE shall withstand and other functional requirements for the period that the WBE will be used; b) construction requirements for the WBE or its sub-components and will in most cases consist of references to normative standards. For WBEs that are pre-manufactured (production packer, DHSV), the focus should be on selection parameters for choosing the right equipment and proper field installation.	Name of specific reference
D. Initial test and verification	This describes the methodology for verifying that the WBE is ready for use and being accepted as part of a well barrier envelope.	
E. Use	This describes proper use of the WBE to ensure that its function is maintained during execution of activities and operations.	
F. Monitoring (regular surveillance, testing and verification)	This describes the methods for verifying that the WBE continues to be intact and fulfils the design criteria.	
G. Common WBE	This describes additional criteria to the above when this element is a common WBE.	

PART I

LITERATURE STUDY AND REGULATORY STANDARDS & REGULATIONS

2. Literature Study

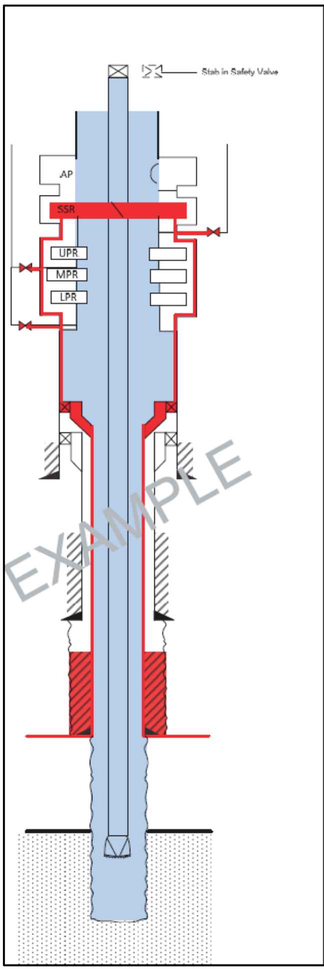
2.1. Well Integrity

According to NORSOK D-010 (2021, p. 10) well integrity is defined as “application of technical, operational, and organizational solutions to reduce risk of uncontrolled release of formation fluids and well fluids throughout the life cycle of a well”. In simpler words, well integrity attribute to having full control of well barriers in an onshore or offshore well at all times.

In order to maintain control over the wellbore, two well barriers shall be functioning throughout the life of the well. There exists two well barriers, primary and secondary, where the primary is the first acting barrier against a potential influx zone, while the secondary barrier functions as a back-up of the primary barrier. For example, in exploration wells and drilling operations, a well barrier refer to having full control of the drilling fluid as this is the primary barrier in several stages. For a well in production, it for example refer to the completion package, i.e., downhole safety valve (DHSV), completion string and fluid, and casing cement.

In well integrity-context there is some important definitions to be aware of. The presented terms and definitions are frequently used in each regulation and recommended practices world-wide and also throughout this thesis. The most common concepts within P&A and well integrity is WBE and well barrier.

Common Well Barrier Element	a shared well barrier between both primary and secondary well barrier.
Permanent Well Barrier	an envelope that extends both vertically and horizontally (full cross section) to form a full zonal isolation.
Primary Well Barrier	the first envelope that prevents potential flow out from the wellbore.
Secondary Well Barrier	the second envelope that prevents potential flow out from the wellbore.
Well Barrier	an impenetrable matter preventing uncontrolled flow of wellbore fluids.
Well Barrier Element	a physical matter that may form a well barrier together with other WBE or by itself.



Well barrier elements	EAC table	Verification/monitoring
Primary well barrier		
Fluid column	1	
Secondary well barrier		
In-situ formation	51	
Casing cement	22	
Casing	2	
Wellhead	5	
High pressure riser	26	
Drilling BOP	4	

Figure 2.1: Example of WBE During Drilling, Coring, and Tripping with Shearable Drilling String (Standard Norge 2021, figure 8)

In Figure 2.1, the primary barrier consists of solely one WBE, and that is the drilling fluid column which is in overbalance with regards to the highest pore pressure in the open hole section. The secondary well barrier consists of several WBEs (in-situ formation, casing cement, casing, wellhead, high pressure riser and BOP) that together forms one well barrier, in this case the secondary well barrier.

2.2. Well Barrier Requirements in PP&A

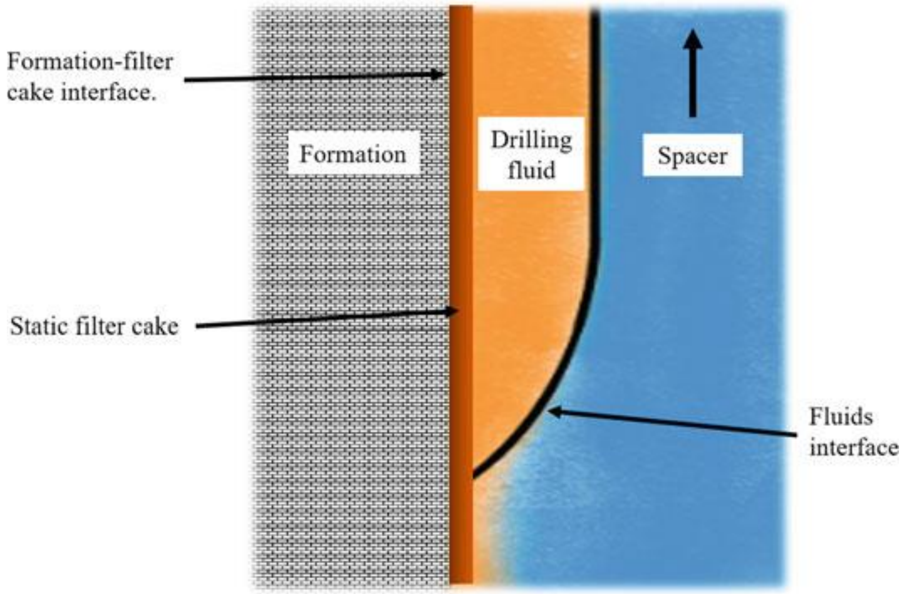
Different regulations and standards have different well barrier requirements. The ultimate goal during PP&A is to restore the properties of the cap rock, and it can therefore be said if any plugging material has similar properties as the cap rock, it can be regarded as competent (Khalifeh M. and Saasen A. 2020, pp. 71-75). A well barrier requirement tells something about the material and functionality required to act as a barrier in PP&A. A material shall have characteristics and verification requirements to be able to qualify as a permanent barrier. Below, the well barrier material requirements are summarized, and those characteristics will be further discussed in the thesis (Khalifeh M. and Saasen A. 2020 p. 71):

- Impermeable, or very low permeability.
- Non-shrinking.
- Long-term durability at downhole conditions.
- Resistance to downhole fluids and gases.
- Non-brittle or ductile.
- Sufficient bonding to casing and formation.

Together with material requirements, permanent barriers also have to follow functional requirements such as downhole placeability, bonding properties, sealing capability, durability, and reparability.

Downhole placeability

A permanent downhole barrier, for example cement, has to displace the existing fluid mediums that is in the wellbore efficiently in order to minimize contamination between the interfaces (Khalifeh M. and Saasen A. 2020, p. 85). To reduce the contamination before pumping the cement, a spacer fluid is pumped ahead to remove residual cuttings, drilling fluid and/or filter cake. A spacer fluid is specifically designed such friction forces from the spacer (ΔP_{f2}) is higher than the bonding force between formation and filter cake (F_{fc}), i.e., $\Delta P_{f2} > F_{fc}$, ref. Figure 2.2.



$$F_{fc} < \Delta P_{f2}$$

Figure 2.2: Spacer Fluid Displacing Filter Cake and Description of Forces (Khalifeh M. and Saasen A. 2020, figure 3.10)

A method to obtain a good barrier placement is to induce turbulent flow for the spacer fluid and cement (Khalifeh M. and Saasen A. 2020, p. 86). Together with turbulent flow, the equivalent circulating density (ECD) increases, and the risk of fracturing the formation goes up.

Bonding properties

Expansion and compression because of bond strength of the plugging material may happen due to differential pressures experienced during the different periods prior to, during, and after setting the plug (Khalifeh M. and Saasen A. 2020, pp. 76-86). Shear bond strength, tensile bond strength, and hydraulic bond strength may induce forces to either the steel or formation. Different downhole conditions, such as differences in material volume, thermal changes, tectonic stresses, and hydraulic forces, may affect the bonding quality, hence the zonal isolation, to such a degree that a leakage may happen.

Hydraulic bond strength is the more important sealing type for zonal isolation intent (Khalifeh M. Saasen A. 2020, pp. 72-75). The hydraulic bond strength is measured either with reference to the pipe or the formation, as described above. By applying pressure on top of a rigid pipe-cement surface and finding the pressure where the cement leaks a fluid through, one has acquired the hydraulic bond strength, ref. Figure 2.3.

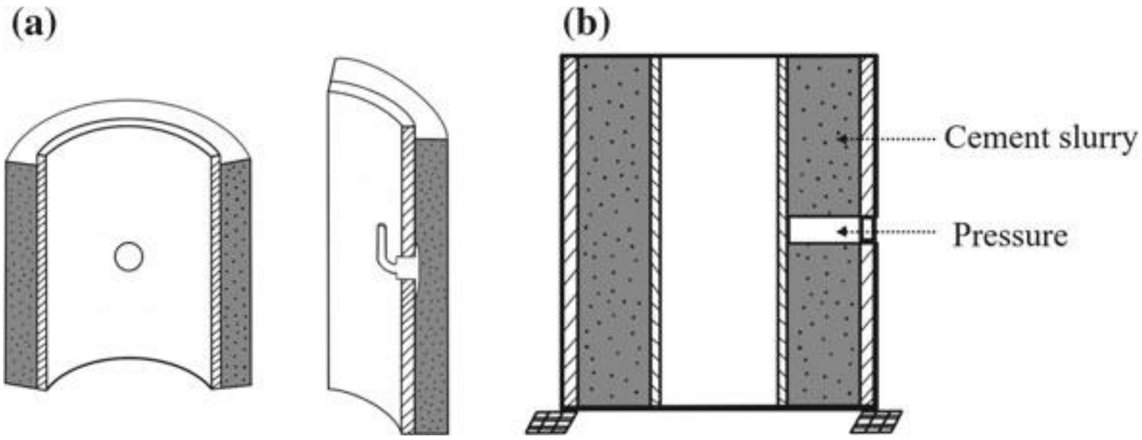


Figure 2.3: Two Examples of Test Setup for Measurement of Hydraulic Bond Test (Khalifeh M. and Saasen A. 2020, figure 3.5)

Sealing capability

As a main purpose, permanent barrier(s) is meant to seal the potential migration and movement of fluids in, up and/or out of the wellbore (Khalifeh M. and Saasen A. 2020, pp. 72-75). The capability a material has to seal is a function of bond strength and permeability. Permeability describes how capable the material is to transfer fluids. All materials are said to have some degree of permeability, where a cap rock's permeability ranges between 1×10^{-3} to 1×10^{-6} millidarcy (mD). In Table 2.1, one can spot permeability for some common materials in the industry.

Table 2.1: Permeability of Some Common Materials (based on Khalifeh M. and Saasen A. 2020, table 3.1)

Material	**Permeability, mD (µD)**
* Portland Cement (class G)	10^{-2} (10)
Granite	$10^{-3} – 10^{-4}$ (1 – 0.1)
Shale	$10^{-3} – 10^{-5}$ (1 – 0.01)
Anhydrites	$10^{-5} – 10^{-7}$ (0.01 – 0.0001)
Halite	$10^{-7} – 10^{-9}$ (0.0001 – 0.000001)

* Pure Portland cement without any permeability-reducing additives, while there is common practice in the industry to add permeability reducing additives in Portland cement.

According to Ramadan MA. et al. (2021, pp. B-C), the bond strength is a function of the cement sheath, subsequently as a consequence of shrinkage and hydration of the cement material. The shrinkage leads to development of micro-annuli and/or cracks in the cement matrix and are considered as a critical property for well integrity over the life cycle of the well, ref. Figure 2.4.

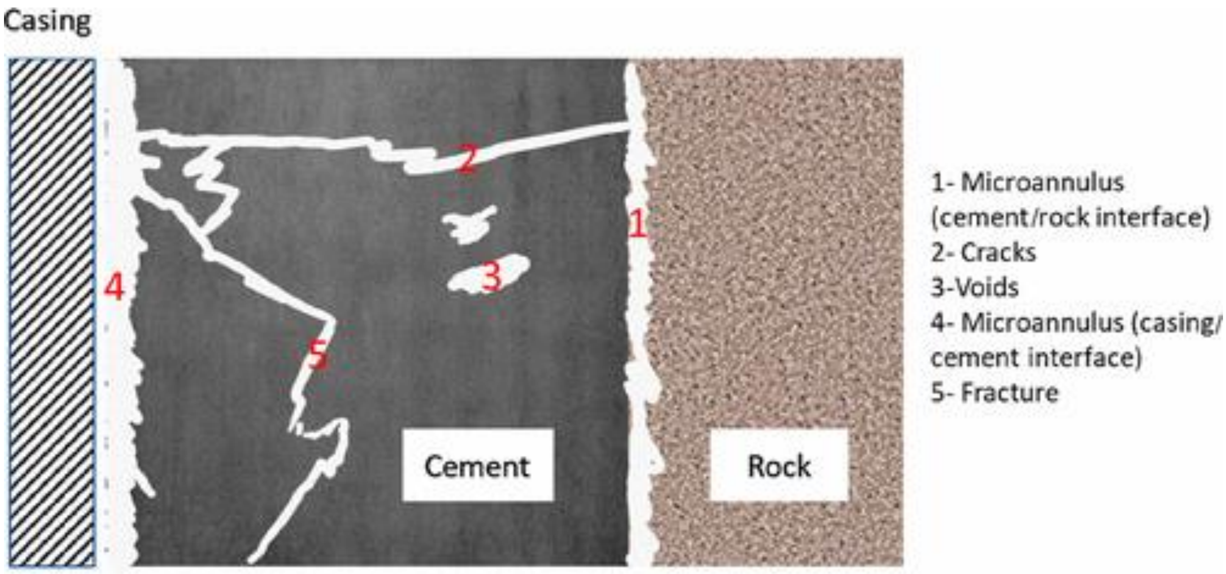


Figure 2.4: Illustration of Cement Micro-Annuli Paths due to Shrinkage (Ramadan MA. et al. 2021, figure 1)

A parametric study exploring the effect of permeability on leakage rate through Portland cement was conducted for permeabilities ranging from 0.1 mD to 0.00001 mD, i.e., 100 µD to 0.01 µD, with one magnitude as increment (Ramadan MA. et al. 2021, pp. E-F). It was assumed a linear micro-annuli of 50 µm based on relevant papers. The flow rate, temperature and cement column in the study was 69 bar, 43°C, and 50 ft (15 m). From Figure 2.5 it is clear that permeability in the cement barrier matrix plays an essential role in leakage rate, hence well integrity for the life of well.

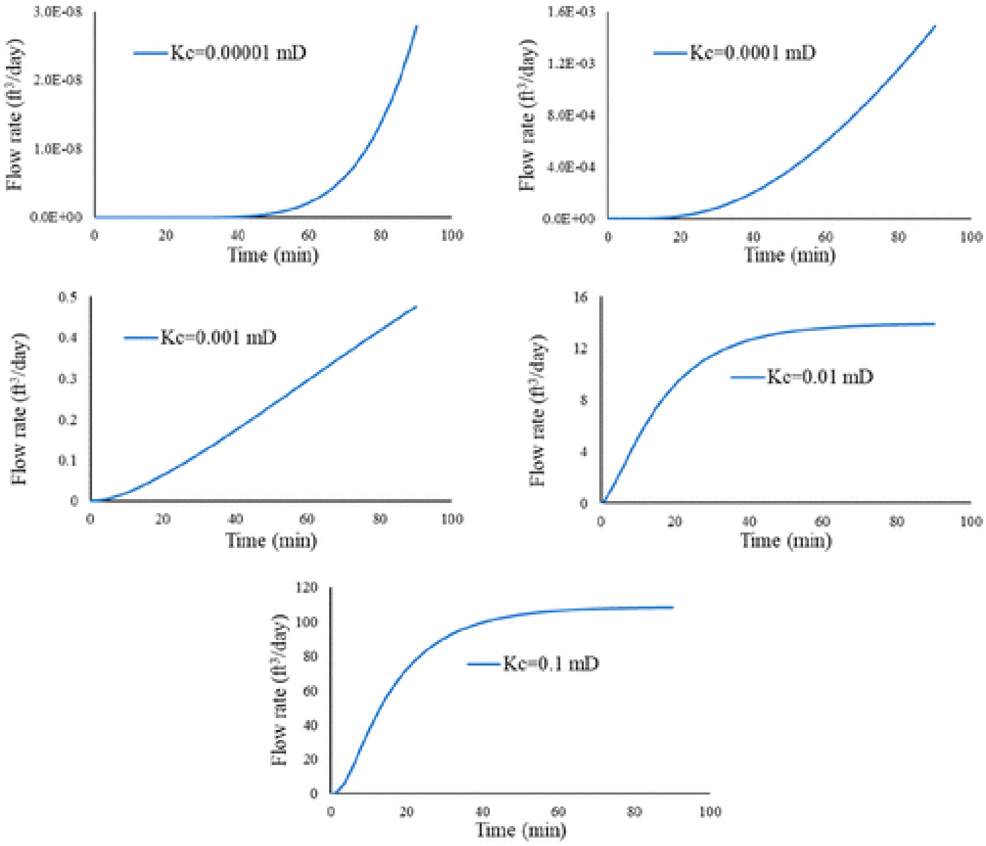


Figure 2.5: Effect of Permeability on Leakage Rates for Portland Cement (Ramadan MD. et al. figure 7)

Durability

Having a durable plugging material means that it should be sustainable and have its initial quality over time with respect to hydraulic conductivity and mechanical integrity (Khalifeh M. and Saasen A. 2020, p. 86). One important aspect regarding durability is to conduct initial aging tests for the plugging material in environments representing the wellbore, i.e., similar fluid types, corrosiveness, pressures, and temperatures. Different regulations and standards have similar principles regarding the durability, but the wording is somehow not the same, and will be discussed in Chapter 3 Barrier Comparison Analysis between Standards.

By conducting considerable experimental studies over a long period of time, the confidence of plugging material used increases (Khalifeh M. and Saasen A. 2020, pp. 87-91). The experimental studies shall contain tests regarding exposure time, downhole condition, wellbore chemicals, microstructure analysis, expansion and shrinkage, weight gain/loss, permeability changes, and material degradation with regards tectonic stresses. Assessing the above properties gives a favourable understanding of how the PP&A-material behaves downhole.

Reparability

When performing a PP&A operation, the intent is to never re-enter the abandoned wellbore (Khalifeh M. and Saasen A. 2020, pp. 91-92). As the wellhead equipment are removed and seabed is cleaned, there are no opportunities to re-enter the wellbore either. This implies that the WBEs should withstand the downhole conditions and not be degrading over time.

2.3. Verification of Permanent Well Barriers

A permanent barrier has to be verified in one or more ways to assure its integrity is functioning (Khalifeh M. and Saasen A. 2020, pp. 204-208). Different methods, in conjunction with each other or alone, can be used to verify the integrity of a permanent barrier; (1) position verification, (2) sealing verification, (3) pressure testing, and (4) weight testing. One can place the permanent barrier either on a fixed fundament, for example a bridge plug, or on a viscous pill, ref. Figure 2.6. Regulations worldwide have verification requirements for different types of barriers as to their integrity, which will be discussed in Chapter 2.4 Regulations, Standards, and Recommended Practices in PP&A and forward.

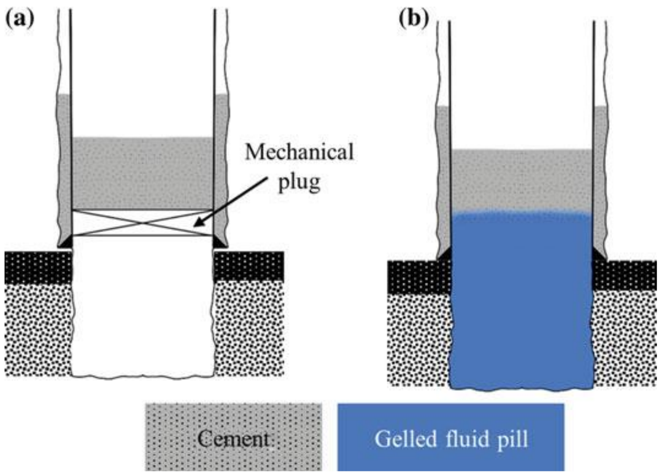


Figure 2.6: Example of a Permanent P&A Barrier on (a) Bridge Plug and (b) Viscous Pill (Khalifeh M. and Saasen A. 2020, figure 7.14)

Position verification (Khalifeh M. and Saasen A. 2020, p. 204) – a way to verify the setting depth of the PP&A barrier by dressing of hard material. For a cementitious material it is used to verify that contamination has not happened, and top of cement (TOC) is confirmed by tagging. In the case where a PP&A barrier has been set on top of a verified mechanical support, there is no need to tag the barrier itself.

Pressure testing (Khalifeh M. and Saasen A. 2020, pp. 204-207) – a way to verify PP&A barriers set inside a casing is to pressure test it up to a pre-defined abandonment design pressure. The barrier can either be placed on top of a mechanical plug or a viscous pill, as shown in Figure 2.6. It is only possible to verify a PP&A barrier inside the casing, and not in open hole. In an open hole-scenario, one would pressure test against the plug in addition to the formation.

If a mechanical plug has passed the pre-defined pressure test value, the PP&A plug on top of the mechanical plug may neglect the test. By choosing this approach, and a good pressure test of the mechanical plug, the company can save time by not waiting on cement (WOC) before pressure testing it.

Weight testing (Khalifeh M. and Saasen A. 2020, pp. 206-208) – a way of verifying open hole plugs, as verifying by use of pressure test in open hole is not possible. This can be done using a drill bit and go down to TOC and applying weight until a few metric tonnes (MT) is set downward. The weight requirement is dependent on the regulatory authorities, ref. Figure 2.7.

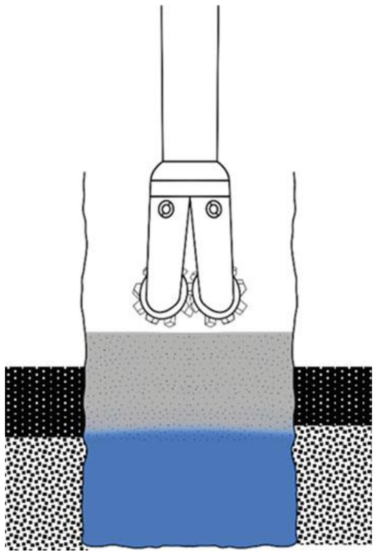


Figure 2.7: A Weight Test of a PP&A Cement Barrier in Open Hole (Khalifeh M. and Saasen A. 2020, figure 7.16)

Sealing verification (Khalifeh M. and Saasen A. 2020, p. 204) – the verification of sealing capabilities is done through both pressure and weight testing. No separate task is required to perform a sealing verification.

In Figure 2.8 below, a flow diagram is shown for the verification of a PP&A plug.

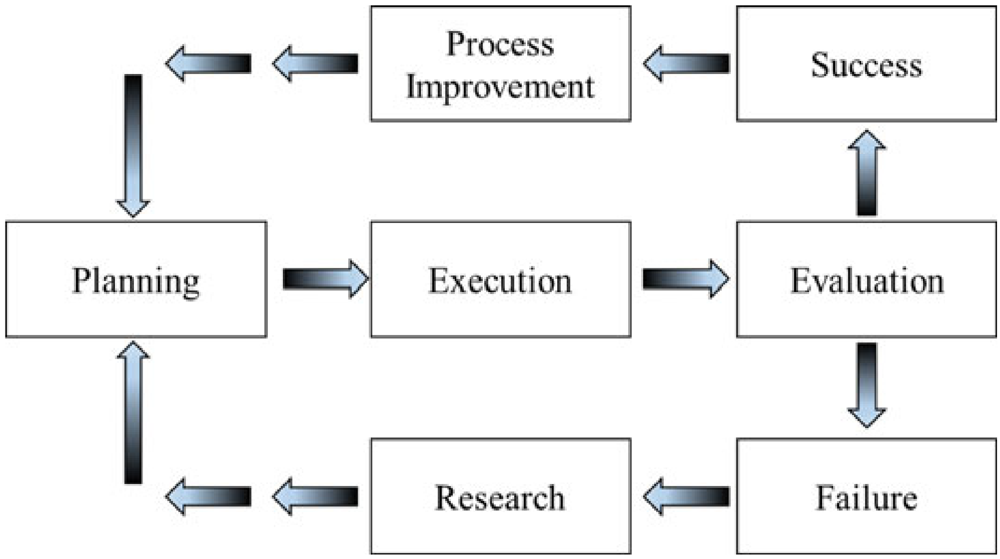


Figure 2.8: Flow of Plug Evaluation Operations (Khalifeh M. and Saasen A. 2020, figure 7.13)

2.4. Regulations, Standards, and Recommended Practices in PP&A

Offshore oil and gas activities in Norway are audited by the Norwegian regulator Petroleum Safety Authorities Norway (PSA), founded in 2004. They set the regulatory requirements for the industry regarding the health, safety & environment (HSE), technical and operational, framework, activities, management, facilities, and working regulations. The regulations from PSA are divided into different guidelines and further refer to recognized standards set in cooperation with industry experts (PSA, 2021). For example, the standard NORSOK D-010 “Well integrity in drilling and well operations” was made by the industry to comply with regulations set by PSA within drilling & wells (D&W) on the Norwegian continental shelf (NCS) and covers all drilling & wells activities included abandonment. The PSA do as a minimum recommend using NORSOK D-010 as a guideline for all D&W operations on NCS.

NORSOK D-010 is one of the four recognized standards within well integrity covered in this thesis that provides expert knowledge, guidance, and sound engineering logic when it comes to P&A and barrier elements. The three others are Oil & Gas UK (OGUK) Well Decommissioning Guidelines, DNV Risk based Abandonment of Wells, and API Wellbore Plugging and Abandonment. Within qualification of materials and new technology, the standards OGUK Guidelines on Qualification of Materials for the Abandonment of Wells and DNV Technology Qualification have been used. A summary of comparative standards and recommended practices (RP) can be found in Table 2.2.

In 2021, DNV GL rebranded to DNV. This is reflected in the standards and references.

Table 2.2: Comparative Standards and Recommended Practices.

Standard / Recommended Practice	Well Integrity and PP&A	Qualification of Materials
NORSOK D-010 Well Integrity in Drilling and Well Operations	X	
OGUK Well Decommissioning Guidelines	X	
API Wellbore Plugging and Abandonment API RP 65-3	X	
DNV Risk based Abandonment of Wells DNV RP-E103	X	
OGUK Guidelines on Qualification of Materials for the Abandonment of Wells		X
DNV Technology Qualification DNV RP-A203		X

The governmental agency in the United Kingdom representing the offshore and onshore oil and gas industry is the Health and Safety Executive, and is similar to the Norwegian PSA. Their equivalent standard to NORSOK D-010 within P&A are OGUK "Well decommissioning guidelines" but OGUK has also developed recommended practices regarding technology qualification of materials specifically for abandonment of wells, OGUK "Guidelines on Qualification of Materials for the Abandonment of Wells".

DNV is an independent company within assurance and risk management and are specialized in several industries including oil & gas. The company is driven by safeguarding life, environment, and property, and supplies standards within oil & gas involving sound engineering coupled with technical assurance. The company has more importantly published recommended practices about risk based abandonment of wells, DNV RP-E103, and technology qualification of materials, DNV RP-A203.

API is an American natural gas & oil standard-setting leader locally in the United States and worldwide. It has standards in all segments of the oil & gas supply chain and are recognized in the industry for delivering a broad range of energy excellence. API has published several recommended practices and the one of interest in this thesis are "Wellbore Plugging and Abandonment", API RP 65-3.

2.5. NORSOK D-010 Well Integrity in D&W Operations

In 2021, the publisher of NORSOK D-010, Well integrity in drilling and well Operations, released a revised version of the industry standard, namely revision 5. The well integrity standard covers well barrier principles, drilling, well testing, completion, production, abandonment, wireline, coiled tubing, snubbing, managed pressure drilling and underbalanced drilling and, pumping activities. It provides general examples throughout the standard with reference to every well integrity scenario. As this thesis will focus on the abandonment part, that chapter together with general well barriers will be described in detail below. NORSOK D-010 rev. 4 was published in 2013. Going further in this thesis, all NORSOK D-010 reference is towards revision 5, if not otherwise stated.

NORSOK D-010 has several specific EAC tables describing well barrier requirements for different cases, as a supplement to the detailed description in each chapter. The relevant EAC-tables in PP&A operations will be discussed, either briefly or in detail, going forward.

This chapter will cover general well barrier principles before describing requirements in the abandonment phase covered in the NORSOK D-010 standard, ref. Table 2.3.

Table 2.3: NORSOK D-010 Chapters Covered

NORSOK D-010 rev. 5 (2021)
3 Terms and definitions
4 Symbols and abbreviations
5 General barrier principles
10 Abandonment activities
Annex C Well barrier elements acceptance tables

2.5.1. Well Barrier Principles

A WBE, according to NORSOK D-010, should be designed such that it is capable to (Standard Norge 2021, p. 17):

- “withstand the maximum differential pressure and temperature it can be exposed to (accounting for depletion or injection regimes in adjacent wells)”;
- “be leak tested, function tested or verified by other methods”;
- “ensure that no single failure of a well barrier or WBE can lead to uncontrolled release of formation fluids and well fluids throughout the life cycle of a well”;
- “re-establish a failed well barrier or establish another alternative well barrier”;

- “operate competently and withstand the environment for which it can be exposed to for its intended service life”;
- “be independent of other well barrier envelopes and avoid having common WBEs to the extent possible”.

A cement plug is only regarded as a common well barrier element if it extends both vertically and horizontally, also illustrated in Figure 1.2 (Standard Norge 2021, p. 18). It is emphasized that cement in the annulus alone is not a definition of a common well barrier element. To create a cross-sectional barrier together with the annulus-casing interface one has to establish a barrier inside the casing also. To create a cross-sectional WBE inside a cased hole, one common practice is to first set a mechanical plug followed by some barrier material on top, as shown in Figure 2.9.

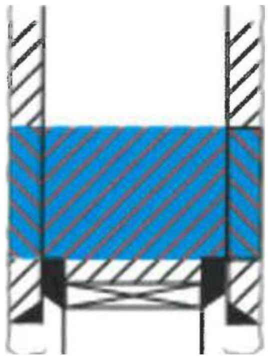


Figure 2.9: Cement in Annulus and inside Casing on Top of Mechanical Plug (Standard Norge 2021, figure 5)

WBEs or well barriers shall as a minimum have its integrity verified by leak testing based on well design pressure (WDP), section design pressure (SDP), a distinct defined differential pressure specified for that WBE, or according to its respective EAC table (Standard Norge 2021, p. 19). The following leak testing should be performed for a case where the EAC table does not specify otherwise:

- A leak test shall be performed “before it can become exposed to a pressure differential in its operating phase”;
- A leak test shall be performed “after replacement of any pressure confining components in a WBE”;
- A leak test shall be performed “when there is a suspicion of a leak”;
- A leak test shall be performed “when an element will be exposed to different pressure/load than it was originally tested to”;
- A leak test shall be performed “if the WBE has been accidentally exposed to differential pressure/load higher than original well design values”.

The acceptance criteria during a leak test are composed by one or several certain requirements (Standard Norge 2021, pp. 19-23). The requirements compose of having acceptable leak rates, testing the leak direction with specified test pressure value(s) and duration, inflow test during both drilling and well activities, performing function testing of the well barriers, formation testing, and finally documenting the performed leak and function of different well barriers. Volumes during leak testing shall be monitored at all times, where possible, for the WBE being tested. A summary of each leak test is given below (Standard Norge 2021, pp. 19-23).

Acceptable leak rates

If not given in the EAC table, the acceptable leak rate, corrected for compressibility, temperature, and volume effects, shall be zero. If there is not possible to monitor the above described, the acceptance criteria should be zero pressure change.

Leak test direction

A leak test shall be performed towards the external environment, i.e., the seabed, to a possible extent. If not practical feasible, it can be performed against the external environment as long as the barrier element is capable to seal in both direction.

Test pressure value

Two pressure tests should be performed; a low and high pressure test. A low pressure test of 10-20 bar shall give stable reading before conducting a high pressure test. A high pressure test has two different definitions; production/injection scenario and abandonment scenario. In the abandonment phase the pressure value shall be 70 bar over the fracture value for the casing of interest at the casing shoe for intermediate casings and below, and 35 bar over fracture value for surface casing and above.

If there are any deviations in the test pressure, this shall be included in the EAC table. The acceptance criteria for a deviation are a declining trend for the pressure change over time.

Test pressure duration

A low pressure test shall minimum be for five minutes. A high pressure test shall minimum be for 30 minutes.

Inflow test

An inflow test is carried out by displacing the well above the barrier to a less dense fluid relatively to the fluid below and make a differential pressure on the barrier itself. It can be performed during drilling, well, and abandonment activities.

Function test of well barriers

WBE(s) shall be function tested:

- prior to installing the subsea or downhole equipment;
- after finalizing installation;
- when irregular loads experienced on the WBE(s);
- after repairing the WBE(s);
- and, periodically according the EAC tables.

Testing of formation	During the drilling phase, rock mechanical data is constantly collected throughout the sections to obtain and verify well integrity. Three different methods can be used as a formation test that is industry standard; formation integrity test (FIT), leak-off test (LOT), and extended leak-off test (XLOT). The formation test shall be documented, and defined, in the EAC table to qualify as a WBE.
Documentation of leak/function testing of well barriers	The responsible person for the operation shall document and accept each well integrity test performed. Documentation shall include specific information, as can be seen in Table 2.4.

Table 2.4: Documentation Criteria for Pressure and Function Testing (Standard Norge 2021, table 4)

Documentation	Pressure test	Function test
a) Field and wellbore name	X	X
b) Proper scale of test chart	X	
c) Type of test	X	X
d) Test/differential pressure	X	
e) Test fluid	X	
f) System or components tested	X	
g) Estimated volume to pressurize system	X	
h) Volume pumped and bled back	X	
i) Time and date	X	X
j) Test evaluation period	X	
k) Observed pressure trend/observed leak rate	X	
l) Acceptance criteria for the test	X	X
m) Result of test (passed or failed)	X	
n) Activation time or turns required for closure of valves		X
o) Signature/date	X	X

It is specified in NORSOK D-010 (2021, p. 30) that failure modes of the primary and secondary WBEs should be evaluated and risk assessed with respect to degradation and escalation causes, reliability, and common failure modes of the primary and secondary WBEs, and a plan to restore, or replace, a degraded well barrier. As the standard state a permanently abandoned well has a retention period of eternity, the risk assessment regarding common failure modes of the primary and secondary WBEs are critical, ref. Table 2.5.

Table 2.5: Well Integrity Records (based on Standard Norge 2021, table 8)

Item	Description	Retention period	Comments
…	…	…	…
11.	Documentation related to how wells are permanently abandoned	Unlimited	Shall include well barrier description, logs, and test charts of tested elements

It is specified that well integrity records have to be documented throughout the well life cycle.

2.5.2. Permanent Well Abandonment Principles

There exist three different types of abandonment principles; suspension, temporary- and permanent abandonment. Chapter 10.4 and 10.5 in NORSOK D-010 covers suspension and temporary abandonment and will not be the focus in this thesis. In suspension and temporary abandonment activities, there is a plan to re-enter the well in a later stage and is therefore not referred to as permanent plug & abandonment, PP&A.

Chapter 10.6 in NORSOK D-010 (2021, pp. 96-111) covers the permanent abandonment part in detail, whereabout guidelines and requirements related to well integrity is the focus. It covers acceptance criteria within well barriers and well barrier elements, gives examples of well barrier schematics, required cutting depths of wellhead equipment, practical examples of contrasting options within permanent abandonment, proposal to establish WBEs in well integrity issues, and design and operational risks.

For PP&A, two barriers, a primary and secondary barrier, shall be established if a zone with flow potential has been drilled through (Standard Norge 2021, p. 97). The exact number of barriers is dependent on the number of zones and if there is potential of flow between them. For example, if several zones within an interval has the same pressure characteristics, they can be regarded as one larger zone. If there is more than one wellbore originating from one slot position, they can share the same well barrier if the shared setting depth can withstand the anticipated pressures, ref. Table 2.6.

Table 2.6: Minimum Number of Permanent Barriers (based on Standard Norge 2021, table 1)

Pore Pressure	Inflow source	Permanent Plug & Abandonment Barrier(s)
Hydrostatic pore pressure	a) Zone has no flow potential nor hydrocarbons.	Not relevant
	b) Zone has no flow potential but contains hydrocarbons.	One*
	c) Zone has flow potential and contains hydrocarbons (for example depleted reservoirs).	Two

	d) Zone has shallow water flow potential (may be locally over pressured).	One
Over pressurized	e) Zone has no flow potential (hydrocarbons or not).	One
	f) Zone has limited potential for flow (hydrocarbons or not, includes shallow water zone).	Two
	g) Zone has flow potential (for example reservoir or shallow water zone).	Two

* In NORSOK D-010 it is specified that it is possible to reduce number of barriers by one if a thorough risk assessment is done yielding an acceptable risk level.

The perspective of permanently abandoned wells shall be eternal and consider differential forces due to drainage, geological processes, and injection/production consequences (Standard Norge 2021, pp. 97-98). During the planning, it shall be considered that virgin pressure can be re-charged and that well barriers shall withstand these pressure changes. For a well barrier to withstand specific pressures, a depth requirement is given by the NORSOK standard, as can be seen in Table 2.7. It is important to note that it is not a requirement to perform a pressure test nor tagging the ‘open hole to surface plug’, also called ‘environmental plug’. The environmental plug is no barrier.

Table 2.7: Well Barrier Depth Requirements (Standard Norge 2021, table 25)

Name	Function	Depth requirement
Primary well barrier	To isolate a source of inflow, formation with normal pressure or over-pressured formation from surface/seabed.	The base of the well barriers shall be positioned at a depth were formation integrity is higher than potential pressure below (see 5.2.3.6.7 FIT/LOT/XLOT methods to determine formation integrity).
Secondary well barrier	Back-up to the primary well barrier, against a source of inflow.	As above.
Open hole to surface / environmental plug	Prevent access to well after casing(s) are cut and retrieved and contain environmentally harmful fluids. The exposed formation can be over-pressured with no source of inflow. No hydrocarbons present.	No depth requirement with respect to formation integrity.

According to NORSOK D-010, and described in Chapter 1.2, a well barrier shall seal in the horizontal and vertical direction, in addition to meet special material properties such as ability to withstand the maximum pressure anticipated from the wellbore and placed at an interval where the rock mechanics has sealing properties with low or nonpermeable characteristics (Standard Norge 2021, pp. 97-98). Where degradation of a tubular may result in loss of well integrity, the tubular shall be removed. This also applies to control line cables; if degradation results in loss of well integrity, they shall be removed. It is emphasized that a plugging material that is planned to be used shall undergo a verification process with documentation.

Table 2.8 describes the well barrier material requirements specified in NORSOK D-010 (Standard Norge 2021, p. 99):

Table 2.8: Requirements for Permanent Barriers (Standard Norge 2021, table 26)

Item	Property	Requirement
a.	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.
b.	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.
c.	Radial shrinkage	For open hole (OH) plugs / OH annular WBEs: low shrinkage. For internal, cased hole WBEs: long-term positive linear expansion.
d.	Mechanical loads	Shall withstand all foreseeable loads in the future. For WBEs exposed to loads outside relevant knowledge/experience envelopes (example: geothermal, injection, high depletion, high pressure tests etc.), Finite Element Analysis (FEA) analysis should be performed and a 40% safety factor in each individual load case should be achieved.
e.	Chemical stability	Withstand exposure to chemicals or substances that can exist without substantially affecting required integrity. Examples: H_2S, CO_2, H_2O, brines, hydrocarbons.
f.	Bonding to tubulars	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, such as expansion, that provides a hydraulic seal to casing and any exposed formation in contact with it.
g.	Effect on tubular integrity	Shall not detrimentally affect properties of tubulars in contact with barrier material.

During drilling, a casing/liner is cemented in place at the casing/liner shoe, where cement is placed in the annulus to case off the formations above the shoe and achieve well integrity to allow further drilling. A FIT, LOT or XLOT is performed before commencing drilling. The cement in the casing annulus is referred to as an external WBE, while cement inside the casing is referred to as an internal WBE (Standard Norge 2021, pp. 99-100). The industry standard differentiate between the external and internal WBEs, whereas the external WBE follows EAC Table 22 and the internal WBE Table 24. According to EAC Table 22, in order to use the annulus cement as an external WBE, the cement interval shall be logged, or, verified by displacement calculations using actual field data. It shall also be performed a FIT, LOT or XLOT to verify well integrity at shoe, according to EAC Table 24, ref. Figure 2.10.

Figure 2.10: Example of External and Internal WBEs at Casing Shoe (External WBE in Green; Internal WBE in Red)

If the external WBE is used both as a primary and secondary permanent barrier, displacement calculations is not adequate (Standard Norge 2021, p. 100). Then, its integrity shall either be documented by logging, or identify two different external WBE that each support the primary and secondary barrier, and pressure test them separately. Pressuring testing them can be done by applying differential pressure across the intervals. If logging, it shall be two intervals of 30 meters measured depth (MD) or more, whereas each interval counts as the primary or secondary WBE.

There is a difference between a documented length of barrier opposed to a planned annulus cement length (Standard Norge 2021, pp. 205-207). One shall during the planning stage not plan for a 30 m MD cement length in the annulus but rather a minimum length of 100 m MD for a casing where no hydrocarbons are expected, or 200 m MD where hydrocarbons are expected when drilling ahead.

The length requirement for a cement barrier that is not in the annulus, as described above, is depending on whether it is set in open or cased hole, also if set on a mechanical fixed structure (Standard Norge 2021, pp. 209-211). An open hole cement plug shall be 100 m MD where at least 50 m MD should be above a potential zone of influx or leakage. If set in a transition zone between the open and cased hole, there shall be at least 50 m MD above and below the casing shoe. A cased hole cement plug shall be no less than 100 m MD unless set on a mechanical fixed structure, then it shall minimum be 50 m MD. When being part of a cross-sectional barrier together with the annulus cement, it shall extend to top of the annulus barrier. See detailed length requirement for each barrier type in Table 2.9.

Table 2.9: Well Barrier Length Requirement (based on Standard Norge 2021, pp. 205-211)

Name	Detailed description	Depth requirement
Annular cement plugs	General, minimum of 100 m MD for one permanent barrier, or a 200 m MD continuous for a combination permanent barrier. If the drilled section penetrated a source of inflow, it shall minimum be 200 m MD above the zone of influx. Annular cement in the production casing shall minimum be 200 m MD. If qualified through use of a cement bond log (CBL) it shall minimum be 30 m MD of good cement.	30 – 200 m MD
Open hole cement plugs	Minimum 100 m MD where minimum 50 m MD shall be above any potential source of inflow. When transitioning between open and cased hole, it shall minimum be 50 m MD above and below the casing shoe.	100 m MD
Cased hole cement plugs	Minimum 50 m MD if set on top of a mechanical structure, or else 100 m MD.	50 – 100 m MD
Environmental plug	Minimum 50 m MD if set on top of a mechanical structure, or else 100 m MD.	50 – 100 m MD

The internal WBE shall be placed inside the wellbore such it covers the whole interval of the external WBE which is verified, i.e., according to length requirement in EAC Table 22 (Standard Norge 2021, p. 100). An internal WBE shall be verified in accordance with EAC Table 24 or EAC Table 55. In short, the material can either be of cement, or an alternative material that has gone through a verification process and deemed acceptable to use as a WBE.

If the length requirements set by the standard cannot be met according to their EAC tables, a comprehensive risk assessment shall be performed, and undergo a sensitivity study on several parameters. If approved on all areas, it can be used as a WBE (Standard Norge 2021, pp. 100-101). For the external WBE, rock mechanical properties may be used to cover for a reduced length of a combined external and internal WBE. A reduced length of the internal WBE can be risk assessed if the external WBE qualifies the length requirement. The risk assessment shall as a minimum include the following:

a) quality and integrity of the cement/plug material;
b) temperature and pressure effects on the material;
c) final and virgin reservoir pressure;
d) potential micro annuli and leak paths;
e) bonding forces between cement/plug material and casing/liner.

In the last decades, two optional contingency methods have been increasingly used; Perf, Wash & Cement (PWC) and casing milling followed by squeezing of cement. Both methods refers to designing the well barrier element according to EAC Table 24 – Cement Plug and can further implement use of EAC Table 55 – Alternative Barrier Material as an alternative, if deemed acceptable according to its element acceptance criteria table requirements.

The end goal of the NORSOK D-010 standard is that a chosen well barrier elements shall withstand all present and future environmental conditions and forces during and after the operation by providing detailed minimum requirements.

2.5.3. Well Barrier Material Definition

In section 3, ‘Terms and definitions’ in NORSOK D-010 (2021, p. 9) the definition of a well barrier element is a “physical element which, in itself, does not prevent flow but in combination with other WBEs form a well barrier envelope” and refer to footnote nr. 2 “Alternative well barrier elements/materials (to traditional mechanical elements, cement, and in-situ formation), can be used when qualified for the applicable conditions, see DNV RP-A203”. The DNV standard Technology Qualification, RP-A203, is an industry recognized recommended practice upon qualification of new technology. This standard will be discussed in detail in Chapter 2.9 DNV Technology Qualification (DNV RP-A203).

2.6. Oil & Gas UK Well Decommissioning Guidelines

In this thesis it has been chosen to focus on the two regulatory standards Well Decommissioning Guidelines (6th issue, 2018) and Guidelines on Qualification of Materials for the Abandonment of Wells (2nd issue, 2015) from OGUK. The standards are according to OGUK "Good practice guidance" and are two of a total of 19 publications. The other publications does not cover the PP&A-phase but rather estimation of cost, breakdown structure, management of marine growth, pipelines etc. Both presented standards are the latest version to date.

The standard from OGUK is meant to provide well operators a risk-based decision-making guideline for wells that are meant to either be temporary or permanently plug & abandoned (UKOOA 2018, p. 9). The P&A standard is focusing on the North Sea region, territorial sea, and onshore areas adjacent to Great Britain and the United Kingdom. It further cover all types of wellbores; explorational, appraisal, and development. The standard focus on PP&A, and not temporary abandonment.

2.6.1. Well Barrier Principles

As stated by the Well Decommissioning Guidelines by OGUK (2018, p. 12) a permanent well barrier in the wellbore must seal both vertically and horizontally. In order to fulfill those requirements, it must have good bonding, adequate barrier length, setting depth in a competent formation, and a type of supporting fundament that prevents migration of gas and cement movement while it is setting, ref. Figure 2.11.

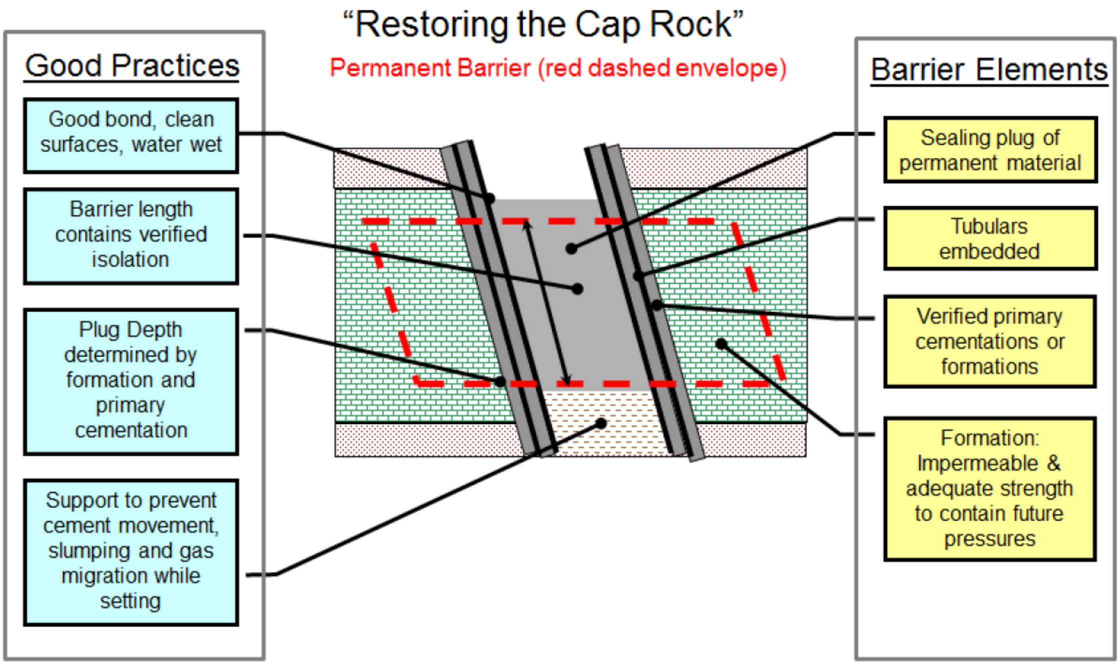


Figure 2.11: Sketch of PP&A Barrier Requirements (UKOOA 2018, figure 1)

A PP&A material shall have the following characteristic (UKOOA 2018, pp. 12-13):

- Long term integrity and over time not deteriorate.
- Be intact at the intended position.
- Be impermeable or have sufficiently low permeability such flow is prevented both through and around the barrier element.
- Withstand mechanical loads, i.e., predictable pressures and temperatures, for "a foreseeable future".
- Full cross-sectional sealing.
- Resist CO_2, H_2S, and other wellbore fluids, and wellbore geology for "a foreseeable future".

The acceptance criteria for qualifying a permanent barrier are composed by one or several requirements (UKOOA 2018, pp. 28-30). Verification of a permanent barrier can be done by tagging, inflow testing, logs, pressure testing, well history, field experience, pumping records, lab testing, sampling, and/or modelling. The usage of one or several verification methods are dependent on the material used, individual well, placement method, and job design. Type of permanent barrier is also distinguished between a wellbore and annular barrier. Summary of the acceptance criteria for permanent barriers are given below.

Acceptable leak rates	Not mentioned in the guideline, should therefore be regarded as zero.
Leak test direction	A leak test shall be performed in the flow direction of the present fluids in the wellbore.
Test pressure value	If a pressure test is used as verification, it should be minimum 500 psi above leak off pressure (LOP) below the barrier but shall not exceed the pressure rating of the casing, included potential damage on casing or wear allowance, whichever is lowest.
Test pressure duration	The duration of pressure test is not specified in the guideline.
Inflow test (drilling/well activities)	The maximum pressure differential that is expected on the barrier should be considered for an inflow test. It can be performed during drilling, well, and abandonment activities.
Function test of well barriers	Function testing of well barriers are not part of the permanent wellbore abandonment guideline from OGUK.
Testing of formation	It should be proved that the formation of interest has the necessary fracture strength in order to resist the maximum foreseeable pressures. Examples of such formation tests are FITs, LOTs, and XLOTs.

Documentation of leak/function testing of well barriers	The responsible person/company for the operation shall document and accept each well integrity test performed. Values and basis for selection shall be included.

A cement barrier, or alternative material(s), functioning as a wellbore barrier must be documented with test values, strength development over time, where it is positioned, volumes, returns, and if tagged (UKOOA 2018, pp. 28-29). The purpose is to verify and document that the chosen barrier prevents flow and can withstand the maximum anticipated pressures. For a cement barrier, this is normally documented first by laboratory tests before the same recipe is used offshore.

A cement barrier, or alternative material(s), functioning as an annular barrier must also be documented in the same manner as a wellbore barrier (UKOOA 2018, p. 29). The verification process is similar to a wellbore barrier, except that tagging is substituted by logging, i.e., cement bond, sonic and/or temperature log. Pressure testing of the annular barrier when drilling out the shoetrack is called a LOT, XLOT, or FIT in a well integrity perspective.

The following shall be documented for a wellbore and annular barrier:

- Volumes and pressures, spacer before/after fluid, cement type and density, and if any, returns and losses.
- Strength development and thickening time for the anticipated downhole pressure and temperature.

2.6.2. Permanent Well Abandonment Principles

Same as the requirement in NORSOK D-010, generally, two barriers, a primary and secondary, shall be established when a wellbore is permanently plugged & abandoned (UKOOA 2018, pp. 13-14). If one zone with flow potential have been penetrated, a minimum of two barriers shall exist. While there is only required a minimum of one barrier if there has not been penetrated any zones with flow potential. Depending on number of potential flow zones and if cross-flow among them are unacceptable, more than two barriers shall be established. The OGUK standard yields more responsibility to the operator to use a risk-based approach when determining required number of barriers for the different zones, ref. Table 2.10.

Table 2.10: Minimum Number of Permanent Barriers (based on UKOOA 2018, p. 13)

Pore Pressure	Inflow source	Permanent Plug & Abandonment Barrier(s)
Hydrostatic pore pressure	a) Zone has no flow potential nor hydrocarbons.	Not relevant
	b) Zone has no flow potential but contains hydrocarbons.	Two
	c) Zone has flow potential and contains hydrocarbons (for example depleted reservoirs).	Two
	d) Zone has shallow water flow potential (may be locally over pressured).	One
Over pressurized	e) Zone has no flow potential (hydrocarbons or not).	Two
	f) Zone has limited potential for flow (hydrocarbons or not, includes shallow water zone).	Two
	g) Zone has flow potential (for example reservoir or shallow water zone).	Two

The OGUK Well Decommissioning Guidelines (2018, pp 12-13) does not mention “eternity” as the perspective of the well barriers like in NORSOK D-010 but rather specify the main characteristics of the material(s) used as a permanent barrier. According to the OGUK standard, the permanent barrier material, which is not limited to cement, shall have certain properties with regards to its permeability, sealing capacity, in-situ capabilities, integrity, and withstand the external environment. According to the guidelines, a barrier material in a wellbore should have the following characteristics, ref. Table 2.11:

Table 2.11: Requirements for Permanent Barriers (based on UKOOA 2018, pp. 12-13)

Item	Property	Requirement
a)	Long term integrity	Not deteriorate over time having key integrity indicators like long-lasting isolation material properties, not de-bonding and cause cracks over time.
b)	Permeability	Shall be impermeable, in this context meaning that permeability is low enough to prevent any flow through the barrier, i.e., being impermeable to flow.
c)	Radial shrinkage	Should be designed to minimise radial shrinkage.
d)	Mechanical loads	Mechanical characteristics suitable to withstand present and future pressures and temperatures.
e)	Chemical stability	It should be resistant to downhole chemicals or substances at foreseeable pressures and temperatures without substantially affecting required integrity. Examples: H_2S, CO_2, H_2O, brines, hydrocarbons, magnesium.
f)	Bonding to tubulars	Should be designed to maximize bonding to tubulars.
g)	Effect on tubular integrity	Shall not detrimentally affect properties of tubulars in contact with barrier material.

Having a material that does not deteriorate over time and maintains its strength while being designed toward present and future pressure and temperatures will together with the other mentioned characteristics above accumulate to an eternity perspective.

A permanent barrier should be of a minimum 100 ft (30 m) in MD above the zone of influx and consist of good cement (UKOOA 2018, pp. 13-14). According to UKOOA (2018, pp. 43-44), good cement is verified through pressure or inflow test. If there exist a cross-flow between two zones with less than 100 ft MD distance from each other, there should be established one barrier as long as practical possible in the interval. From the standard, the two permanent barriers can be combined into one combination barrier, meaning that it is two permanent barriers set continuously, ref. Figure 2.12. A combination barrier shall therefore be minimum 200 ft MD (60 m) of good cement above the zone of influx, twice as much as one.

In order to achieve 100 ft of good cement, it is advised that up to 500 ft MD (150 m) of cement should be planned for, while 800 ft MD (250 m) should be used to achieve 200 ft MD of good cement and form two PP&A barriers (UKOOA 2018, p. 23). During the planning stage one can optimize the planned cement length by considering the wellbore conditions, i.e., offset experiences, inclination, verification method, and wellbore environment.

If no logs are planned to be used to qualify an annular barrier, they shall also be planned with longer cement intervals during drilling and cementing of the casing (UKOOA 2018, p. 29). Rather than using logs to qualify the cement in annulus, one or two permanent cement barriers can be planned with respectively up to 500 or 1,000 ft MD (300 m). Also in this case, a thorough evaluation of wellbore environment shall be conducted to finalize required length of cement barrier.

Table 2.12: Minimum Well Barrier Length Requirement (based on UKOOA 2018, pp. 13-17)

Name	Detailed description	Minimum Depth requirement
Annular cement plugs	Generally, minimum of 100 ft MD (30 m) for one permanent barrier, or a 200 ft MD (60 m) cumulative for a combination permanent barrier. If the drilled section penetrated a source of inflow, it shall minimum be 200 ft MD (60 m) above the zone of influx. Annular cement in the <u>production casing</u> shall minimum be 200 ft MD of good cement (60 m).	30 – 60 m MD 100 – 200 ft MD
Open hole cement plugs	Minimum 100 ft MD (30 m) where minimum 50 ft MD (15 m) shall be above any potential source of inflow. When transitioning between open and cased hole, it shall minimum be 50 ft MD (15 m) above and below the casing shoe.	30 m MD 100 ft MD

Cased hole cement plugs	Minimum 100 ft MD (30 m) either set on top of a mechanical structure or extended from open hole.	30 m MD 100 ft MD
Environmental plug	No requirement.	-

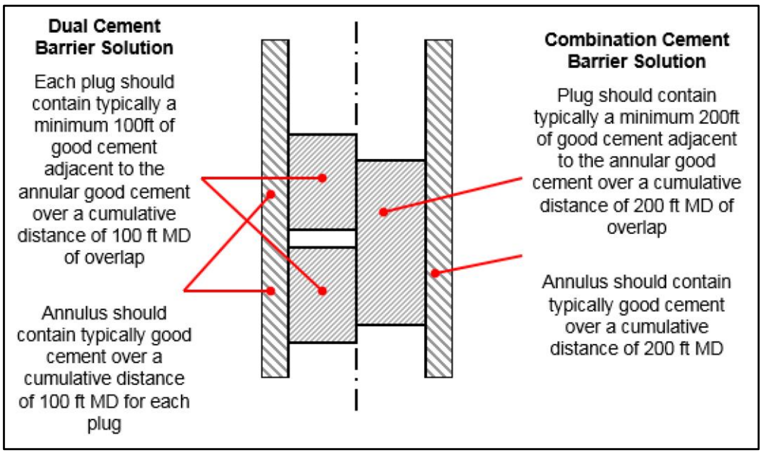


Figure 2.12: Example of [LEFT] two Separate Permanent Barriers in Casing, and [RIGHT] a Combination Permanent Barrier in Casing (UKOOA 2018, figure 2)

A primary permanent barrier shall be situated 100 ft above the zone of influx in a competent cap rock with mentioned characteristics and if feasible, it should be placed such it is possible to set a new primary permanent barrier without removing the first one (UKOOA 2018, pp. 16-17). One may use the secondary permanent barrier to support the primary one, in addition to have it as the functioning primary barrier for another influx zone if a suitable cap rock is present between the interval. For example, if a zone B was permanently plugged with a primary barrier, and a second influx zone A was situated 200 ft above, one can set zone B's secondary barrier just above zone A and it will function both as a secondary and primary permanent barrier, as seen in Figure 2.13.

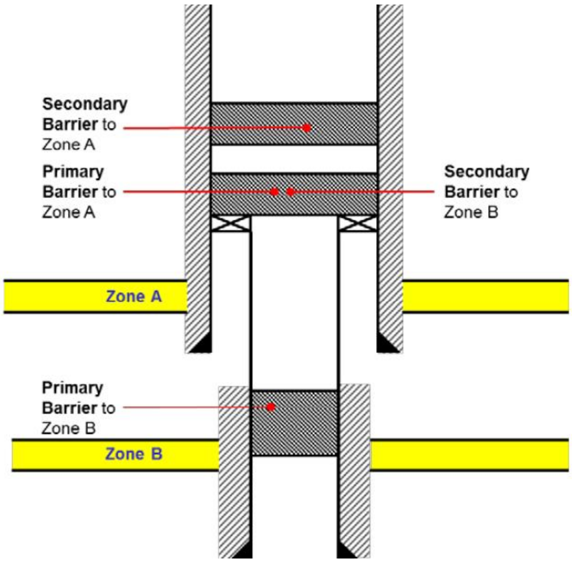


Figure 2.13: Example a Permanent Barrier Function as a Primary and Secondary Barrier inside Casing (UKOOA 2018, figure 3)

The shown example above is situated inside a casing string with cement in the annulus, but this principle is similar to if set in open hole. It is recommended to extend an open hole permanent barrier to inside the casing to allow a pressure test of the plug and verify its integrity (UKOOA 2018, p. 17).

If the mentioned characteristics of a permanent barrier is achieved, different equipment downhole can be formed as a part of the barrier itself (UKOOA 2018, p. 25). Production wells for example have tubing, packer, control lines, and tubing debris, and if they do not comprise the integrity of the permanent barrier, they can form part of it. It shall be risk assessed the consequences of the scenario with regards to leak paths, degradation of equipment, failure modes, and which type of equipment that forms a part of the barrier. Having allowance for different equipment in the barrier is an advancement from the last revision of the guideline.

The PWC and casing milling contingency options are described in Appendices C "Cement Barrier Placement – Potential Issues and Mitigations" but the guideline does not mention it otherwise than there. It elaborates on the potential issues one may experience and possible mitigations against it. The guidelines still has the same requirements regarding barriers despite choosing the PWC or section casing milling options

End goal of the OGUK Well decommissioning guidelines is the same as of NORSOK D-010, to have safe guidelines describing requirements for permanent well barriers.

2.6.3. Well Barrier Material Definition

Section 3.2, "Material Requirements for Permanent Barriers" in OGUK Decommissioning Guidelines (2018, pp. 12-13) reference OGUK Guidelines on Qualification of Materials for the Abandonment of Wells but no reference to NORSOK or DNV standards. The standard states that a well barrier material is not limited to cement but should have certain characteristics. Throughout the Well Decommissioning Guidelines, cement is referred to as the permanent barrier material, but it does not categorize it into specific types of cement.

Section 3.4.4 "Alternative Materials" (UKOOA 2018, p. 15) recognize the need of new technological developed PP&A materials. Before an alternative material can be used, it shall go through a qualification process. OGUK have made a separate guideline regarding the technology qualification of new materials for abandonment of wells, which will be gone through in detail in Chapter 2.10 Oil & Gas UK Guidelines on Qualification of Materials for the Abandonment of Wells.

2.7. API Wellbore Plugging and Abandonment

API released a new recommended practice for wellbore PP&A operations in June 2021 to support safe and efficient plugging, that is API RP 65-3, Wellbore Plugging and Abandonment. It gives guidance on how to seal a wellbore to mitigate against fluid migration by covering applications and operating environment, barrier material considerations, installation techniques, and evaluation and verification criteria. Examples are given for different cases with reference to contrasting plugging scenarios.

2.7.1. Well Barrier Principles

A barrier is defined as "a component or practice that, if properly installed, contributes to the total system reliability by preventing liquid or gas flow" (API 2021, p. 3). Materials used as a barrier element shall posess the following:

a) "no degradation of sealing capacity over time during the period of abandonment;"
b) "appropriate for environment and application;"
c) "inability for wellbore fluids to bypass in either direction whether through or across;"
d) "avoidance of movement".

A wellbore barrier should seal cross-sectionally and recreate a seal similar to the original natural seal that initially prevented migration of hydrocarbons (API 2021, pp. 5-6). Development of a cross-sectional seal can be seen in Figure 2.14.

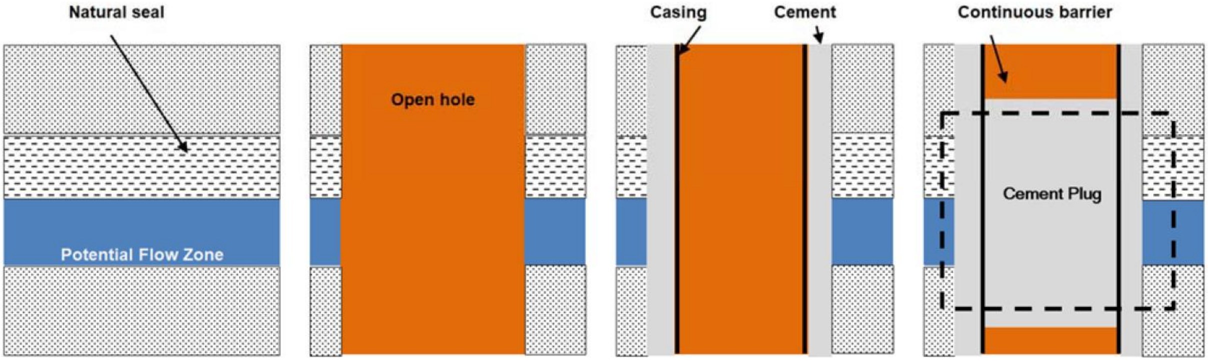


Figure 2.14: Natural Seal vs. Reactivating the Seal (API 2021, figure 2)

When possible, a barriers setting depth and integrity should be verified, where the verification method is dependent on whether it is in annulus, cased hole, or open hole (API 2021, pp. 26-27).

Table 2.13: API Barrier Verification Practice (API 2021, pp. 26-27)

Name	Evaluation & Verification Method
Annular cement plugs	Surface parameters: • Pump rates, fluid density, pressures, volumes, placement method, material properties etc. Tests: • Pressure test, formation integrity tests, CBL and/or annular communication tests.
Open hole cement plugs	Surface parameters: • Pump rates, fluid density, pressures, volumes, placement method, material properties etc. Tests: • Tagging and applying weight with drillpipe, and/or tagging with wireline.
Cased hole cement plugs	Surface parameters: • Pump rates, fluid density, pressures, volumes, placement method, material properties etc. Tests: • Pressure test (positive or negative), tagging and applying weight with drillpipe, and/or tagging with wireline.

There should be established an acceptance criteria for each type described above; annular, open hole, and cased hole cement plugs (API 2021, pp. 13-15). A track-record of cement evaluation logs and pressure test operations from a “few” wells shall be included in the acceptance criteria and if deemed acceptable, less verification methods may be used. Below, a description of the acceptance criteria used in API RP 65-3 are given.

Acceptable leak rates No wellbore fluids should be capable to bypass the barrier, i.e., acceptable leak rates are zero.

Leak test direction A leak test can be performed in both direction, i.e., an inflow or hydraulic pressure test.

Test pressure value A pressure test should be performed after a potential cement evaluation log has been conducted. No specific testing values are given.

Test pressure duration No duration for pressure tests are given.

Function test of well barriers No detailed function testing is given for wellbore barriers.

Testing of formation Formation testing should be performed to verify its integrity and sealing capabilities in order to obtain information if it can withstand pressures from below and above. No detailed are given regarding type of test.

Documentation of leak/function testing of well barriers Documentation should be done and further define the acceptance criteria for such wellbore environments.

2.7.2. Permanent Well Abandonment Principles

API RP 65-3 Wellbore Permanent Abandonment covers suspension, temporary-, and permanent abandonment but the main focus lay within permanent abandonment. By visualising general examples for different P&A scenarios it guides the reader on how to perform safe and risk-based plugging of wellbores.

No specification regarding having two permanent barriers, a primary and secondary, is given in the recommended practice by API but alternatively includes that in one of the example figures, as can be seen in Figure 2.15 (API 2021, p. 7). Two cross-sectional permanent barriers are set to seal the potential flow zone. It includes in-situ formation, annulus cement, casing, and cement inside the casing.

The primary goal should be to isolate zones that has potential for flow, that being hydrocarbon zones, over pressurized water zones, either natural or induced, and shallow gas zones (API 2021, p. 5). According to API, zones with hydrostatic pore pressure, i.e., zones where pore pressure is not higher than the wellbore pressure, is not relevant in the PP&A standard. There is not any recommendations on numbers of barriers in the API standard, ref. Table 2.14.

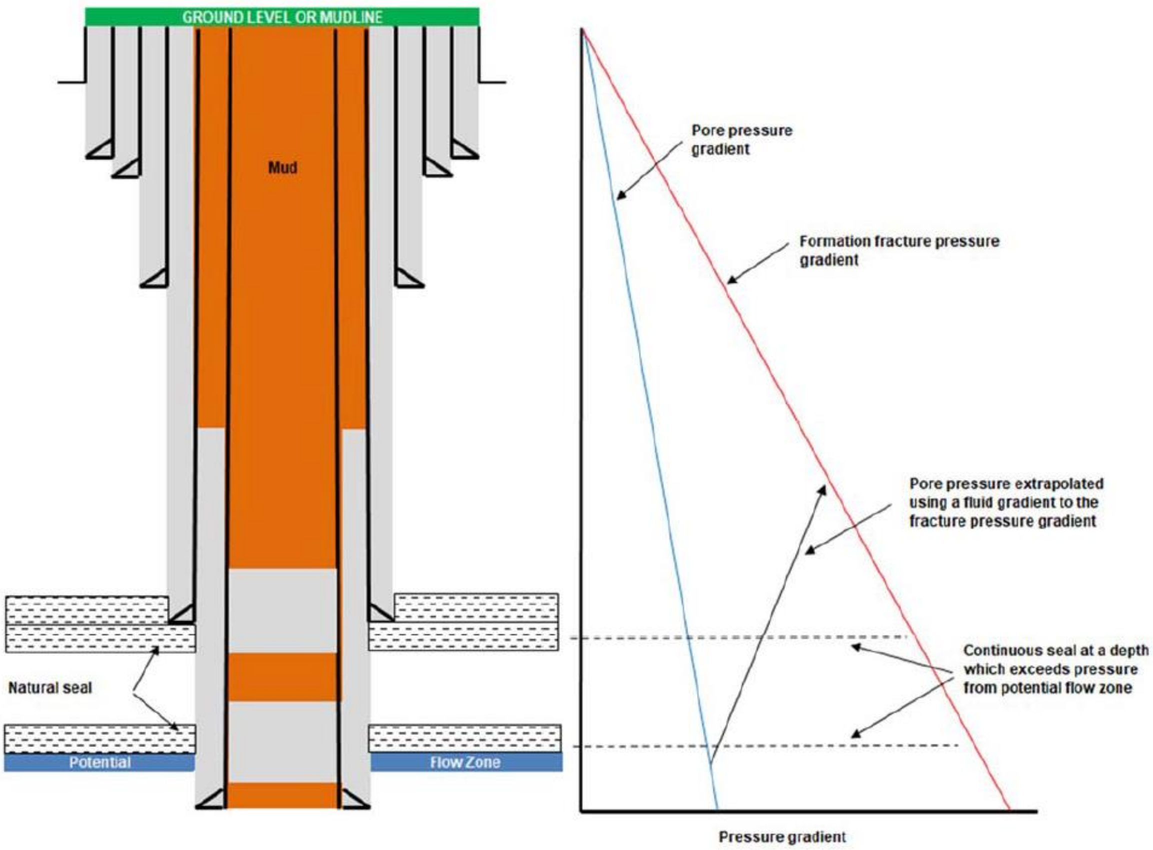


Figure 2.15: Example of Two Permanent Barriers (API 2021, figure 3)

Table 2.14: Minimum Number of Permanent Barriers (based on API 2021, pp. 1-43)

Pore Pressure	Inflow source	Permanent Plug & Abandonment Barrier(s)
Hydrostatic pore pressure	a) Zone has no flow potential nor hydrocarbons.	N/A
	b) Zone has no flow potential but contains hydrocarbons.	N/A
	c) Zone has flow potential and contains hydrocarbons (for example depleted reservoirs).	N/A
	d) Zone has shallow water flow potential (may be locally over pressured).	N/A
Over pressurized	e) Zone has no flow potential (hydrocarbons or not).	N/A
	f) Zone has limited potential for flow (hydrocarbons or not, includes shallow water zone).	N/A
	g) Zone has flow potential (for example reservoir or shallow water zone).	N/A

The lifetime perspective of permanently set barriers are according to API RP 65-3 (2021, p. 14) for “the planned service life and the anticipated well environment”, mentioned multiple times in the guideline. A barrier with the characteristics described in Chapter 2.7.1. Well Barrier Principles accumulates in properties that has a longevity similar to eternity.

A permanent barrier shall be placed in an interval where surrounding geology reactivates a continuous seal together with the barrier in addition to being able to withstand the pressure differentials from above and below (API 2021, pp. 5-6). In addition to prevent any contamination to seabed or surface, it shall prevent contamination of water resources that persist in the wellbore.

The contrasting characteristics a permanent well barrier shall posess are summarized in Table 2.15.

Table 2.15: Requirements for Permanent Barriers (API 2021, pp. 12-15)

Item	Property	Requirement
a)	Long term integrity	No key indicators except long durability as a result of low permeability, and porosity are given to comply with a long term integrity.
b)	Permeability	As low permeability as Portland cement or persistent with the cap rock it replaces. No specific values given.
c)	Radial shrinkage	No requirements regarding shrinkage mentioned but rather that the material shall not degrade over time and lose its sealing capability. Not differentiated between open hole or cased hole barriers.
d)	Mechanical loads	Shall withstand the operating environment.

e)	Chemical stability	Barrier materials should withstand exposure from common chemicals and micro-organisms. Common chemical exposure includes CO_2, H_2S, completion fluids, produced fluids and other wellbore fluids.
f)	Bonding to tubulars	A barrier set in a tubular area may introduce a new flow path if the steel gets degraded over time, and considerations shall be done for this case. If applicable, TOC should be above a casing/tubing stub.
g)	Effect on tubular integrity	Not described.

No differentiation between external and internal WBE are recognized in API RP 65-3 and how an external WBE shall verify its well integrity to be used as part of the permanent well barrier. There is described in Chapter 4.2.2. in the guideline that the formation integrity should be able to withstand such pressure differentials expected and a method to verify such is by use of FIT, LOT or XLOT.

A permanent barrier plug length is not quantified in the guideline but rather refer to regulatory requirements (API 2021, p. 21). Certain recommendations are given, such as rig capability, consideration of reducing length and set multiple plugs to minimize risks.

2.7.3. Well Barrier Material Definition

Cement is used as a reference case throughout API RP-65-3 (2021, pp. 12-13), where cement is defined as being any material, or a combination of different materials, that is a fluid and can be used as a sealing medium. Different barrier material classifications may be appropriate for sealing purposes, such as mechanical-, natural-, or chemical-based ones. Examples are Portland cement, geopolymers, hardening ceramics, pozzolan blends, phosphate cement, blast furnace slag blends, resins, or other suitable materials. Each classified material has individual limitations or restrictions that should be considered when assessing the applicability of a barrier material in a given wellbore environment.

It is specified in the guideline that potential local regulatory requirements shall supersede the any recommended practice given by API RP-65-3 (2021, p. 13).

2.8. DNV Risk based Abandonment of Wells

In September 2020, DNV published a revised version of their recommended practice (RP) 'Risk based abandonment of wells', DNV-RP-E103. It is meant to provide a risk based, sound engineering guidance to abandon onshore and offshore wells while both make time and cost more efficient (DNV 2020, pp. 6-7). Using barrier and risk management, this recommended practice is designed to aid new technology to allow smarter solutions and ultimately reduce cost. It shall give wells and P&A engineers together with risk analysts tools and techniques to perform thorough evaluation of wells that have already been abandoned, and, if any, identify improvement points. According to DNV-RP-E103 (p. 6), the following main barrier and risk principles comprises of:

- "Assessment principles for formations with flow potential."
- "Confirming compliance with safety criteria for the field/installation."
- "Determining the functional and performance requirements for permanent well barrier materials."
- "Differentiating the environmental risk exposure relative to hydrocarbon composition."
- "Establishing site-specific safety and environmental risk acceptance criteria."
- "Identifying, describing, and managing uncertainty."

These main barrier and risk principles may be implemented as a support for quantitative decision-making

2.8.1. Well Barrier Principles

A WBE, according to DNV-RP-E103, should be designed such it is fit-for-purpose for the intended application, in addition to consider wellbore environment effects that is reasonably foreseeable (DNV 2020, pp. 14-15):

- Withstand all present and future anticipated loads a barrier may be exposed to.
- Behave as intended in different temperatures, pressures, stresses, and fluids.
- Avoid unacceptable flow of hydrocarbon to the environment.
- Avoid unacceptable flow between formations, included water-bearing ones.
- Remain reliable and robust to achieve long-term integrity.

The recommended practice from DNV does not specify how a well barrier shall as a minimum have its integrity tested but rather recommends using a risk-based approach to determine potential for loss of containment (DNV 2020, p. 12). The risk acceptance criteria can be divided into two groups; environmental risk acceptance criteria and safety risk acceptance criteria. By using a risk-based approach, one minimizes threats to environment and safety through quantitative assessment by using defined acceptance criteria.

An environmental risk acceptance criteria is based on the external ecosystem, i.e., exposure of hydrocarbons to identified threatening places (DNV 2020, p. 20). Different environmental exposure areas can be sea sediments, water column, sea surface, potential habitats on seabed or surface, and fish. It is recognized in the RP that normal seawater may have background THC (Total Hydrocarbon Content) and in such case, those parameters shall be included in the environmental risk acceptance criteria.

For safety risk acceptance criteria, wells are classified based on consequences in an adverse safety issue (DNV 2020, p. 20). It is differed between subsea and platform wells after a well is permanently abandoned; for a subsea well the safety risk might not be relevant, while for a platform well the safety is highly relevant. To comply with the safety risk acceptance criteria, the plugged well should control formations that is hydrocarbon-bearing in the wellbore.

2.8.2. Permanent Well Abandonment Principles

DNV-RP-E103 (pp. 14-15) categorizes a hydrocarbon-bearing formation into three different levels; no or limited, moderate, or significant potential for flow. Prior to commencing permanent abandonment activities, it should be established an overview of such potential zones throughout the wellbore in order to make risk-based approaches. For the designated flow types, DNV recommends that number of independent well barriers should be based on a thorough risk analysis and required reliability level.

Table 2.16: Minimum Number of Permanent Barriers (based on DNV 2020, table 2-1)

Categorization of potential flow	**Definition**	**Number of well barriers**
None or limited potential for flow	Hydrocarbon-bearing formation with mobile hydrocarbons in the present or future that will **not** have any impact on the environment or safety under all circumstances.	0 to 1.
Moderate potential for flow	Hydrocarbon-bearing formation with mobile hydrocarbons in the present or future that **may** have an impact on the environment but **not** on safety.	1 to 2.
Significant potential for flow	Hydrocarbon-bearing formation with mobile hydrocarbons in the present or future that **may** have an impact on both environment and safety.	2.

A wellbore that may be exposed to a zone with moderate to significant amount of flow with potential environmental consequences should be abandoned according to the as low as reasonably possible (ALARP) principle (DNV 2020, p. 14). The ALARP principle is a risk-based approach, where a potential catastrophic outcome is weighed against probability of such event. ALARP is commonly used in industries to maximize safety while decreasing time and money spent.

As stated in the RP from DNV, if practical feasible, a primary and secondary well barrier should be independent, but they can also be combined and not be independent (DNV 2020, p. 15). If choosing a combination barrier, it must be as reliable and effective as two independent barriers. Such analysis shall be quantitative. In addition to wellbore barriers, one environmental plug should be set close to surface to isolate the wellbore itself. Three examples of scenarios can be seen in Figure 2.16, Figure 2.17, and Figure 2.18.

In Figure 2.16, a reservoir with limited flow potential that has been penetrated through. Due to a limited flow potential, the DNV RP recommends using a single wellbore barrier situated above the zone for PP&A. There is included a separate environmental plug at the top.

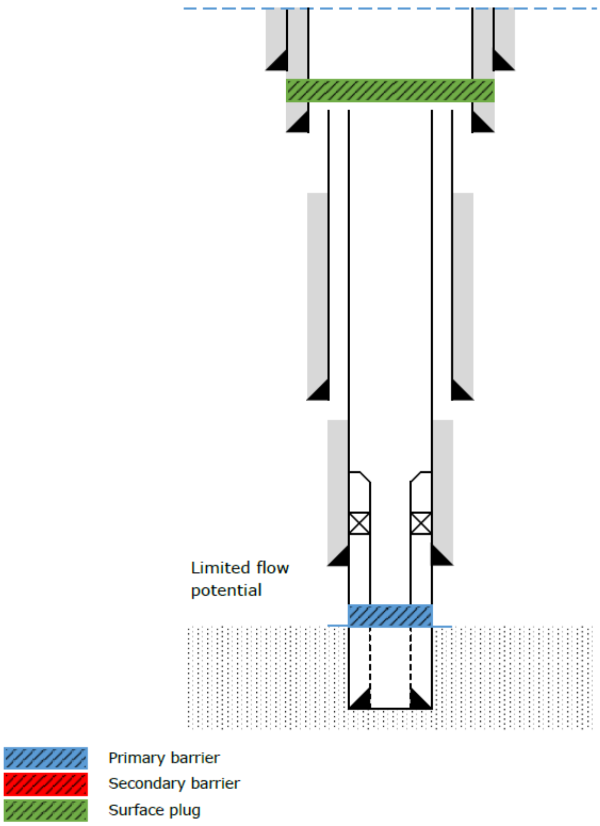


Figure 2.16: Example of PP&A for one hydrocarbon-bearing zone with limited potential for flow (DNV 2020, figure 3-2)

Figure 2.17, in this case, there is two zones with moderate flow potential; one at the true depth of the well and a second mid-way. Note that the above penetrated zone has been cased of and cemented from the shoe to above the zone with moderate flow potential. Two primary and secondary barriers have been used to PP&A the wellbore. There is included a separate environmental plug at the top.

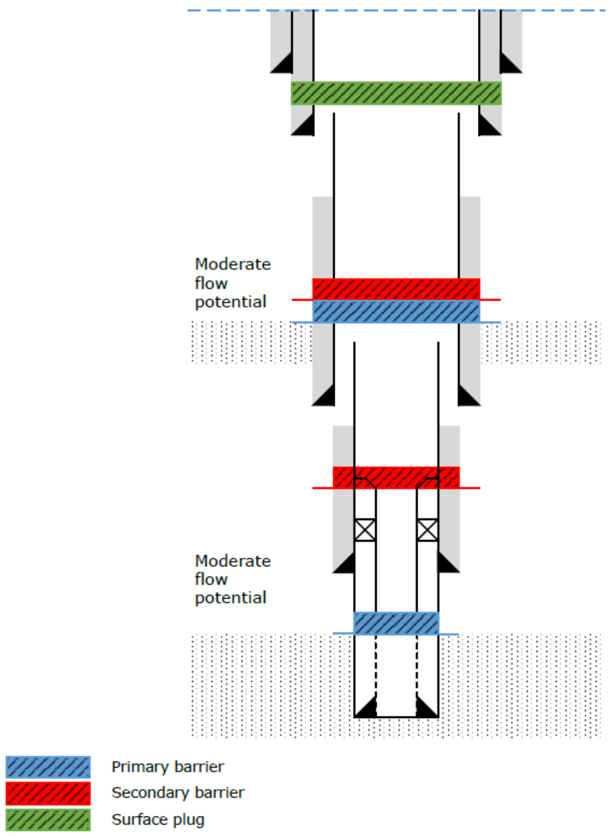


Figure 2.17: Example of PP&A for two hydrocarbon-bearing zones with moderate potential for flow (DNV 2020, figure 3-3)

Figure 2.18, the third example from DNV, two zones with flow potential; bottom one with moderate flow potential and middle one with limited flow potential. The above penetrated hydrocarbon-bearing zone is cased and cemented from the shoe to above the zone with limited flow potential in this case also. There is only established a primary and secondary barrier for the bottom zone while no additional barrier is set for the zone with limited flow potential.

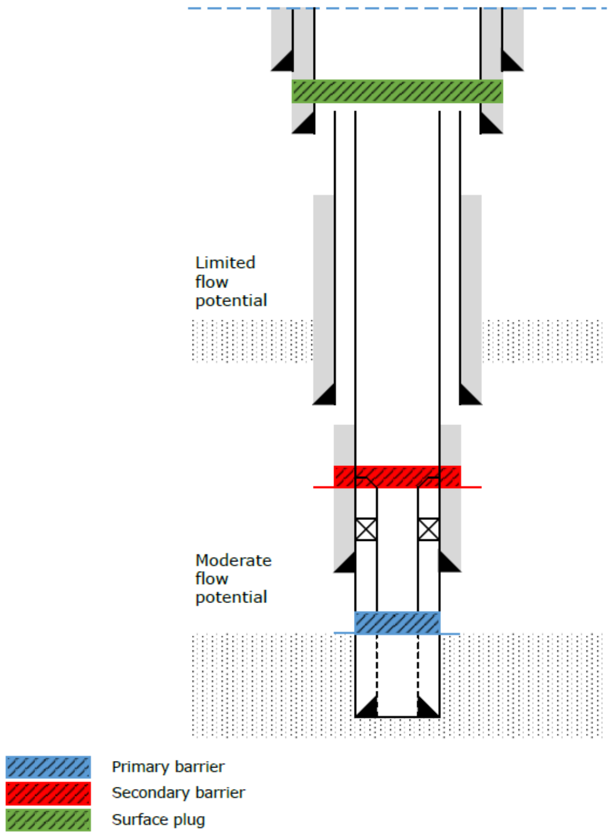


Figure 2.18: Example of PP&A for two hydrocarbon-bearing zones with limited and moderate potential for flow (DNV 2020, figure 2-4)

The surrounding formations adjacent to the permanent well barrier should form part of the barrier element, in other words meaning it has to seal both vertically and horizontally (DNV 2020, p. 15). To seal horizontally, a barrier element shall be placed beside an impermeable formation, and to create a vertical seal it shall be placed at a depth where integrity of the formation can withstand pressure from below and above, i.e., be intact at the set depth.

Table 2.17 describes the well barrier material requirements specified by DNV in “Risk based Abandonment of Wells” (2020):

Table 2.17: Requirements for Permanent Well Barriers (based on DNV 2020, table B-1)

	Potential failure mode	Potential failure mechanism	Strategy for risk management
Mainbore	Insufficient length of barrier in mainbore	• Miscalculations of density. • Slippage of barrier. • Identified top of barrier being too low.	In the quantitative models, the assessment of required barrier length should be included.
	Degraded barrier function in mainbore	• Permeable barrier. • Inaccurate density of barrier. • A micro-annulus may be formed due to higher porosity in the barrier which is a result of barrier shrinkage.	Sensitivity studies should be performed for the potential of flow around and through the barrier(s).

		• Operational problems.	
Casing	Corrosion of casing	• Long or short term exposure of wellbore fluids.	Sensitivity studies should be performed for the potential of flow around and through the barrier(s). Define the time frame and surrounding formation properties.
	Yielding of casing caused by pressure in wellbore	• Loads from formation. • Geological forces acting on well over time.	
Annulus	Insufficient length of barrier in annulus	• Slippage because of inadequate losses or density. • Not possible to do a squeeze job.	In the quantitative models, the assessment of required barrier length should be included.
	Degraded barrier function in annulus	• Corrosion due to H_2S. • Corrosion due to CO_2. • Previously present micro-annulus. • Previously present channels. • De-bonding and/or thermal cracking because of the Joule-Thomson effect when injecting a fluid into reservoirs that is depleted. • Poor bonding and/or channelling. • Degradation due to magnesium-chloride.	Sensitivity studies should be performed for the potential of flow around and through the barrier(s).
	Contamination of barrier in annulus	• A micro-annulus may be formed due to higher porosity in the barrier which is a result of barrier shrinkage. • Poor removal of filter cake and cutting creates a potential hydrocarbon path where flow may migrate.	
Formation	Formation overpressure	• Nearby injection points. • Pressure build-up with time.	Evaluation of the respective formation properties and surrounding environment with regards to cross-flow and seepage.
	Exposure of fluid	• Degradation with time.	
	Geological formation as barrier	• If feasible, formation may be used as an additional barrier.	Classify aquifers and/or compact formation to form a permanent barrier.

The approach from DNV is general in nature as it is understood that every well is not of same character and need a risk-based way of determining the level of barrier requirement. Every well differ in their pressure regime, flow potential, amount of flow zones, and wellbore condition, either old, new, bad or good. By following the DNV standard in conjunction with more specific PP&A standards such as NORSOK D-010, OGUK, and/or API, one can combine barrier requirements and have a risk-based approach that will ultimately reduce time and cost.

2.8.3. Well Barrier Material Definition

In the recommended practice from DNV, a specific barrier material is not defined but rather that the material itself shall have the functionalities described in Chapter 2.8.1 Well Barrier

Principles. Cement is only referred to as an annular barrier but not for open or cased hole barriers.

2.9. DNV Technology Qualification (DNV RP-A203)

The DNV recommended practice for technology qualifications (2019) is a supporting document providing industries a systematic way of proceeding when qualifying new technology for use. It covers everything from smaller components to bigger systems, and is a more general document opposed to the specific by UKOOA (2015) on qualification of materials for PP&A. By using specific operational limits together with acceptable confidence levels, it provides an evidence criteria for a new technology. The DNV recommended practice shall set the basic principle for how to conduct a technology qualification.

Using a risk-based approach to qualify the usage of new technology, it yields a reliability interval for specific limits. Through numerous qualification steps, a technology may be deemed acceptable for use within its specified field. DNV can issue an industry recognized Statement of Certificate to the supplier with acknowledge the technology.

2.9.1. Qualification and Documentation Procedure

To implement the technology qualification steps, there is necessary to have a novel approach regarding associated failure modes and how functional terms are applicable and complete (DNV 2019, p. 18). From the recommended practice, a general approach is as described below:

- A systemic and risk-based approach should be the basis for the technology qualification process, in addition to being performed by a team that has the required expertise.
- Screening of the technology shall be done for the different elements, as the highest uncertainty lies within the elements. Uncertainty may be towards the operating environment, its usage, or the technology itself. The technology qualification shall aim attention on the different mentioned elements.
- If the uncertainties are significant, sensitivity analysis for the qualification process should done to find and adjust if deviations found.
- Potential failure modes shall be detected, and their criticality shall be assessed based on risk and consequence.
- Failure modes which is not detected may present a risk. This risk shall be mitigated by having the correct competencies, challenging the proven and assumptions by performing component test and small to large scale trail tests.
- Different technology elements that is not novel shall be verified independently with pre-defined requirements, for example applicable specifications and/or standards.

- The achievements in the qualification process shall be enough to cover the uncertainty for the technology meeting functional specifications such as performance, safety, and reliability. With increasing uncertainty, higher safety margins can be established, or more achievements shall be done. End goal is to reduce uncertainties such it meets an acceptable level.
- When possible, the qualification basis shall be based on analysis in order to fulfil the scope of requirements (DNV 2019, pp. 26-27).
- Evidence of the qualification process, based on expert judgement, shall be traceable and documented.
- Discussion if a quality assurance, quality control (QA/QC)-process should be implemented for assembly, manufacturing info, installation, start-up, inspection, commissioning and decommissioning, repair, equipment and/or components shall be detailed in the technology qualification process if deviating from given specifications and/or standards.

When a novel approach has been implemented, it shall be established a technology qualification process, that is compromised of the following steps (DNV 2019, pp 24-25):

- A qualification basis including requirements to establish.
    a) Type of technology, planned use, and expectations.
- Assessment of the technology; possible restraining obstacles.
    a) Focus on area with highest uncertainty and key challenges.
- Assessment of the threat; risks and failure modes.
- Plan for the qualification; choosing a method for the specific technology.
- Execution; collect and document the data.
    a) Lab tests, small to large scale tests, experience, and numerical analysis.
- Is the set requirements in step (1) met?
    a) Yes: Technology is qualified.
    b) No: Modifications of the technology needed.

Summary of a general technology qualification process is described in Figure 2.19.

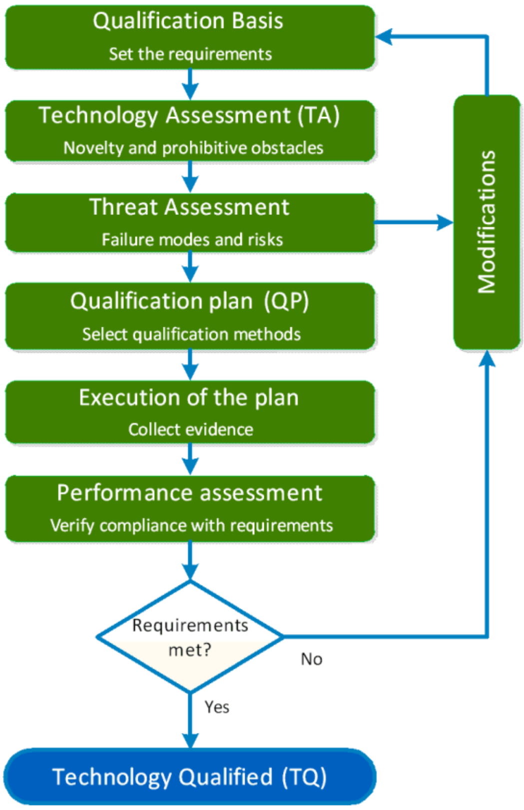


Figure 2.19: General Technology Qualification Steps (DNV 2019, figure 5-1)

For technologies it is often required to investigate not one but numerous failure modes and see if they influence each other by adjusting their parameters (DNV 2019, p. 25). Through iterations, one by one failure mode should be eliminated, and new knowledge is gained. Number of iterations needed during the qualification step is dependent on factors as boundary conditions, technology change and/or improvements done during the process, and performance expectations and/or reliability of the technology, ref. Figure 2.20.

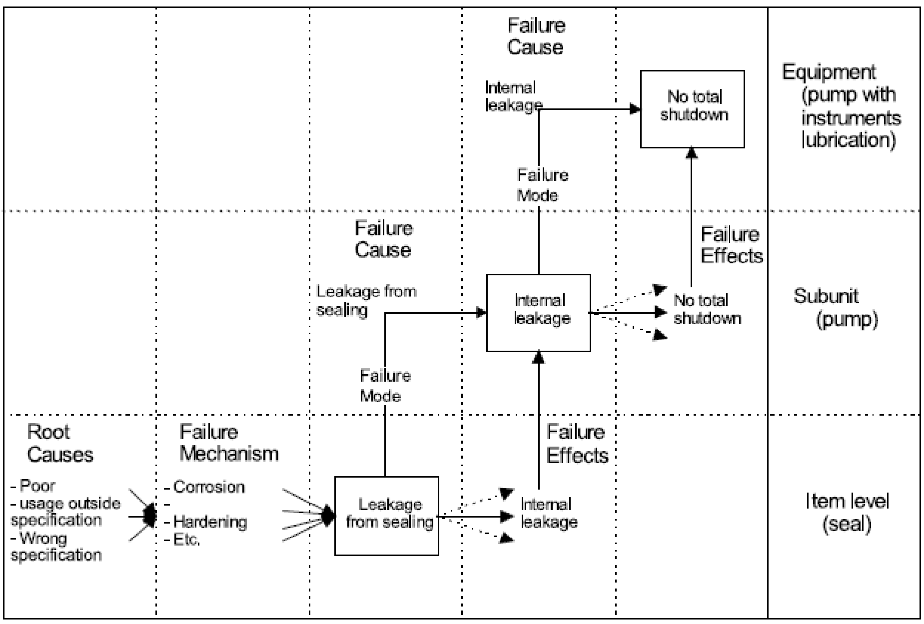


Figure 2.20: Example of Failure Mode Root Causes on a Pump (DNV 2019, figure 8-1)

An essential part of the qualification process is experiments ultimately aiming to prove the suitability of the technology (DNV 2019, pp. 44-47). In order to prove evidence that the technology is applicable in the environment it is supposed to operate, a technology qualification plan shall be established describing the detailed plan for every test planned carried out, which properties and possible failure modes to assess, limiting values for the technology, and reasoning for the chosen experiments. The eminent source of evidence is through documented experiments, for example in peer-reviewed papers published by recognized bodies.

The last step in the qualification process is the performance assessment, which conclusively is this thesis document (DNV 2019, pp. 52-54). By reviewing the available information against the regulatory and institutional standards as a basis for the technology qualification, one can measure if the available technology meets the necessary requirements with regards to an acceptable risk and uncertainty level. If there still exist uncertainties within the technology, one can carry out a performance assessment including a judgment of the uncertainty and risk whether it is acceptable or not to have an early implementation of the novel technology.

2.9.2. Proposed Materials

With regards to cementitious materials, the DNV recommended practice for technology qualification (2019) does not enclose any specific information for the subject. The industry recognized standard for qualification of materials in the PP&A-phase published by OGUK will be described in detail in Chapter 2.10. Oil & Gas UK Guidelines on Qualification of Materials for the Abandonment of Wells. In sub-chapter 2.10.2. Proposed Materials, relevant materials in PP&A will be detailed.

2.10. Oil & Gas UK Guidelines on Qualification of Materials for the Abandonment of Wells

OGUK have published a separate document describing the minimum criteria for technology qualification of materials used in PP&A (2015). By assisting throughout the technology qualification, it ensures well integrity and isolation of formation and/or wellbore fluids from migrating to seabed or surface. The guidelines shall set the standard in the industry for well operators when designing PP&A activities with alternative materials. By nature, it is goal setting and complies with the recognized UK Offshore Installations and Wells Regulations (SI 1996/913) and OGUK Well Decommissioning Guidelines. The OGUK guideline refer to the recommended practice from DNV (DNV RP-A203) and implements the same qualification process and documentation practice used.

The industry-accepted material for permanent barriers in PP&A is Portland G-class cement (UKOOA 2015, p. 6). Other cement types based on Portland cement have been used in the recent decades, where additives have been added to resist the different downhole conditions, whether it is high temperature or pressure, sour or bitter environment, and/or gas, oil, or water reservoir.

2.10.1. Qualification and Documentation Procedure

For a permanent barrier material that is planned to be used in the field it shall undergo the following technology qualification steps, implemented from DNV RP-A203 to comply with regulatory standards such as NORSOK D-010 and OGUK Well Decommissioning Guidelines (UKOOA 2015, p. 16).

- A systematic approach should be the basis for the qualification process.
- One shall identify the failure modes of the material and weigh it against the risks, i.e., using the consequence and probability of a material failure.
- There shall be established an “experimental work plan”, i.e., several measurements and tests of the barrier material.
- If practical possible, analysis and theoretical calculations of the barrier material should be recorded and documented, and further verified through function tests.
- It shall be demonstrated and documented that the manufacture and distribution of the material achieve the specification specified in the experimental work plan.

The above described technology qualifications steps shall go hand-in-hand with the described principles below:

- Functional and specification requirements shall be quantitative.
- It shall be established limits for the capability and failure modes by use of recognized standards or methods, or a mix of both describing the uncertainty in the data used, calculations, operation, and tests.
- In the case where previous experience is used as validation of limits, a documentation describing this must be performed.
- Recognized literature or field tests shall describe the practical parameters and critical limiting material.

Summary of the technology qualification process is described in Figure 2.21 below.

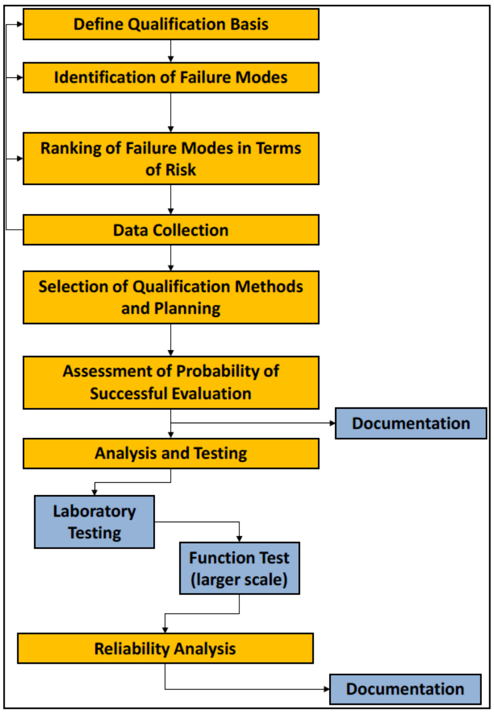


Figure 2.21: Qualification of New Material Process (UKOOA 2015, figure 3)

When applicable, documentation of the qualification process shall include the following (UKOOA 2015, pp. 18-19):

- Material manufacture and installation information:
  a) Certificates of the material.
  b) Samples of the material, and where they are stored.
  c) Record of the manufacturing process.
  d) Record of the installation process.
  e) Record of the personnel qualifications.

- Analysis:
    a) Estimate of the minimum lifetime describing the assumptions and used extrapolation procedure.
    b) Analysis of the failure modes.
    c) Tally of all assumptions made during assessment of the failure modes.
    d) Description of parameters or conditions that has not been evaluated or tested in the technology qualification process.
    e) Determination of the operational envelope for the material.
- Documentation of fundamental equipment during the qualification process:
    a) Justification and description of used methods and tests.
    b) Reliability of the used system.
    c) Documentation of parameters, conditions, results, number of tests, and, if any, failures with description.
    d) Limiting values from the tests and analysis, i.e., maximum, and minimum values.
    e) Key conditions and parameters at start of the experiment.
- Criteria for design:
    a) Anticipated results from each test including quantified acceptance degrees.
    b) Reference to standards, guidelines, and regulations used together with justification.
    c) Justification of used test parameters.
    d) Justification of selected experimental tests.
- Revision historic:
    a) A record shall be established with history of revisions for documents made.

Potential root causes of a failure mode may be a function of one or several things; leakage in the barrier element around the material, leakage in the barrier element through potential porous medium, and a change in the position of the barrier, either vertically or horizontally (UKOOA 2015, pp. 26-33). In Chapter 2.5.1, the requirements for a permanent well barrier is described, and shall be adhered to in the technology qualification procedure.

2.10.2. Proposed Materials

A list of potential suitable permanent barrier material is listed based on their material substance, physical nature, and chemistry (UKOOA 2015, pp. 34-36). Materials that are not listed in Table 2.18 is not part of the guidelines scope.

Table 2.18: Potential Material Types for Permanent Barriers (based UKOOA 2015, p. 34)

Type	Material	Examples
a)	Cements/ceramics (setting)	Portland G-class cement, phosphate cements, pozzolanic cements, hardening ceramics, geopolymers.
b)	Grouts (non-setting)	Clay or sand mixtures, barite plugs, bentonite pellets, calcium carbonate and similar inert particle mixtures.
c)	Thermosetting polymers and composites	Epoxy, resins, vinyl esters, polyester, also including fibre reinforcements.
d)	Thermoplastic polymers and composites	Polypropylene, polyethylene, polycarbonate, polyamide, PVDF, PEEK, PTFE, PPS, also including fibre reinforcements.
e)	Elastomeric polymers and composites	Natural and silicone rubbers, swelling and PUE rubbers, polyurethane, nitrile, neoprene, FFKM, FKM, EPDM, also including fibre reinforcements
f)	Formation	Salt, shale, and claystone.
g)	Gels	Silicate-, polymer-, and clay-based gels, diesel/clay mixtures, starches, and polysaccharides.
h)	Glass	N/A
i)	Metals	Steel, and other bismuth-based alloys.
j)	Modified in-situ materials	Barrier materials that is formed through formation and/or casing as a result of chemical or thermal modification.

Certain properties of the material are critical and is directly linked to its failure modes. There is a requirement that a barrier material holds the essential properties for the specific application it is used for. A detailed description of different properties are listed in Table 2.19 (UKOOA 2015, pp. 35-36).

Table 2.19: Material Properties and Possible Failure Modes (based on UKOOA 2015, table 3)

Property	Definition	Significance
Absorption	Mass of a liquid invaded in pore space within a material. Units: % of volume or mass.	Indicates amount of swelling of the barrier, allowing further estimation of stresses. Also provide a basis for calculation of permeability.
Chemical resistance	Whether the material chemically reacts with the surrounding fluid(s). Denoted as resistant, limited resistant, or not resistant. Units: None	Indicates if the material properties will change, and at what degree, depending on environment around the barrier.
Cohesion	A materials granular strength characteristic indicating strength of cementation between grains when shear stress forces acting. Units: Pa = Nm^{-2}.	Enables shear failure calculations for barrier material, which is a function of tensile strength.
Creep	Linear deformation under mechanical loads over time. Units: Elongation as %/sec.	Enables estimation of the total change of a barrier in different environments and ultimately shrinkage.
Decomposition temperature	A specific temperature where the barrier material starts decomposing thermally. Units: $C°$ at a set environment.	Enables judgment at which downhole temperatures the barrier material will degrade.

Density	Mass pr. Unit volume. Units: kg/m^3.	Enables QA/QC imbalance testing on how the material will behave opposed to the other fluids in the wellbore.
Diffusion coefficient	Constant of how a materials flux moves proportional to diffusion, where concentration is the gradient determining the diffusion process. Units: m^2s^{-1}.	Enables calculations at which rate a barrier will release a fluid through a determined length of barrier material based on lag time among breakthrough and placement at an estimated concentration differential.
Fatigue life	Amount of stress cycles a material can withstand before causing a fatigue failure. Units: N_f.	Enables predictions of the life for the barrier in a specific stress regime.
Hardness	Capability to resist being penetrated through or deformed on its surface. Units: None.	QA/QC can be performed prior to utilizing material. Some material has a relationship between hardness and shear yield strength.
Hydrostatic yield	Hydrostatic stress level where plastic deformation begins. Units: $Pa = Nm^{-2}$.	Enables predictions of pore collapse for the material. Cohesion, a materials bond strength, will irreversible be weakened below this level.
Internal friction angle	A materials granular strength ability to resist shearing stress. Units: Degrees.	Enables calculations of the effect of increased particle size for a barrier material.
Modulus of elasticity	Quantity measuring a materials ability to withstand an elastic deformation. Ratio of the stress and strain forces acting on the material. Units: $Pa = Nm^{-2}$.	Enables calculations at which degree the material will start to irreversible deform under a pressure differential and thermal expansion.
Permeability	A materials ability to transfer a fluid on or through its surface area Units: Darcy.	Enables calculations at which rate a barrier will release a fluid through a determined length of barrier material based on lag time among breakthrough and placement at an estimated pressure differential.
Poisson's ratio	Deformation of a material perpendicular to the loading forces acting on it. Ratio of radial and axial strain. Units: None.	Enables lateral deformation calculations for a barrier under the exposed pressure and temperature environment.
Shear bond strength	Shear stress where the bonding between interfacing materials fails due to shear loading. Units: $Pa = Nm^{-2}$.	Enables calculations of how much shear stress a material can resist due to differential pressure before it fails.
Tensile bond strength	Tensile stress where the bonding between interfacing materials fails due to tensile loading. Units: $Pa = Nm^{-2}$.	Yields maximum tensile loads a material can resist before it fails.
Tensile strength	Tensile stress a material can withstand before it ruptures. Units: $Pa = Nm^{-2}$.	Yields maximum tensile stress the material can resist.
Unconfined compressive strength	Axial compressive stress a material can withstand before it ruptures. Units: $Pa = Nm^{-2}$.	Yields maximum axial compressive stress the material can resist.
Volume change	Changes in material volume. Units: % of pre and post volumes.	Enables calculations whether a material will shrink or expand when setting.

3. Barrier Comparison Analysis between Standards

A comparison between the recognized standards will be presented based on the theoretical review concluded in Chapter 2. Literature Study. The main focus will be within the barrier requirements and material perception within each one. Specifically, focus will be on definitions of barriers and whether a barrier element in PP&A is defined to be Portland cement or equivalent.

The four different well integrity standards covered ranges in their requirement and detail level, as NORSOK D-010 and OGUK Well Decommissioning Guidelines being the two with in-depth detail and coverage, and API Wellbore plugging and abandonment and DNV risk based abandonment of wells giving a more risk-based view with more room for interpretation.

3.1. NORSOK D-010 Rev. 5 and Rev. 4

NORSOK D-010 rev. 5 (2021) and rev. 4 (2013) has several changes within WBE's and PP&A requirements. In summary, it has introduced use of alternative barrier materials with detailed reference to type of qualification process it shall undergo and requirements for first-time usage.

From rev. 4 to rev. 5, the covered chapters have been interchanged. See details in Table 3.1.

Table 3.1: NORSOK D-010 rev. 4 and rev. 5 Chapters

NORSOK D-010 rev. 4 (2013)	NORSOK D-010 rev. 5 (2021)
3 Terms, definitions and abbreviations	3 Terms and definitions
4 General principles	5 General barrier principles
9 Abandonment activities	10 Abandonment activities
15 Well barrier elements acceptance tables	Annex C Well barrier elements acceptance tables

A full comparison have been done and is attached in Appendix A12 Detailed Barrier Comparison of NORSOK D-010 rev. 4 and rev. 5. The most significant change with regards to material usage is described in Table 3.2 below.

Table 3.2: Barrier Material Comparison of NORSOK D-010 rev. 4 and rev. 5

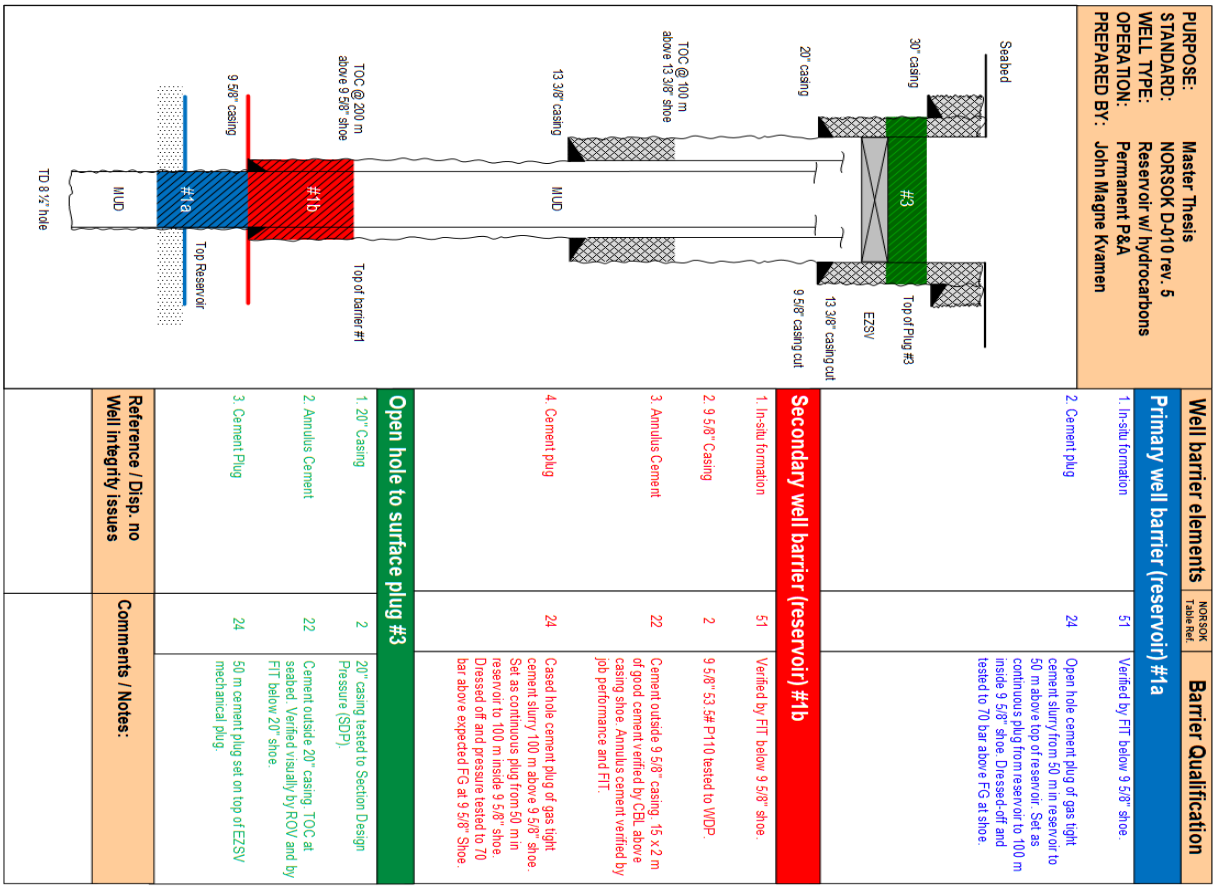
NORSOK D-010 rev. 4 (2013)		NORSOK D-010 rev. 5 (2021)		Differences between standards
Topic	**Description**	**Topic**	**Description**	**Comments**
3 Terms and Definition – Cement	"Collective term for cement and non-cementitious materials that is used to replace cement"	3 Terms and Definition – Cement	Removed.	An unclear description of cement was removed in rev. 5. Has instead been implemented in the definition of a Well barrier element, see topic below.

3 Terms and Definition – Well barrier element	Definition of a well barrier element.	3 Terms and Definition – Well barrier element	Definition of a well barrier element. Note 2: Alternative materials/WBE's may be used when a qualification procedure has been done for the relevant material.	A supplement, Note 2, to the definition was added. It replaces the general definition of cement that was included in rev. 4 and says that an appropriate qualification process similar to the one described in DNV RP-A203 shall be established before it is used in field.
WBE Acceptance Criteria Table (EAC) 55 – Material plug	Describes a general material plug and refer to the minimum material plug lengths for open hole, cased hole, and surface.	WBE Acceptance Criteria Table (EAC) 55 – Alternative barrier material	Describes barrier requirements for materials other than Portland-based cement. a) Refer to using OGUK Guidelines on Qualification of Materials for the Abandonment of Wells, or similar, for the qualification process of new materials. b) For materials used in PP&A it shall fulfil requirements in Table 2.6 – Requirements for Permanent Barriers. c) For an alternative material being used for first time in a well, the same qualification process should be used during installation offshore/onshore. d) An acceptance criteria shall be established for the specific alternative barrier material used. e) Monitoring is required for a first-time usage of the alternative material.	The EAC table in rev. 4 has been re-defined into taking new alternative barrier materials into account, to follow the technological advancement happening in the industry as whole. Referencing OGUK Guidelines on qualification of materials for the abandonment of wells and DNV RP-A203.

Subsequently, the considerable change from rev. 4 to rev. 5 in NORSOK D-010 is towards definitions of cement and well barrier elements, and the establishment of a qualification process for alternative materials, referencing both to the DNV technology qualification (2019) and OGUK guidelines on qualification of materials for the abandonment of wells (2015).

For example, by following the qualification process recommended in NORSOK D-010 for one specific alternative material that is approved barrier wise and holds the required well integrity specified, one can introduce the alternative material for barrier usage in PP&A, in addition as a general well barrier in supplementary well operations.

The minimum barrier requirements for PP&A have hardly changed from rev. 4 to rev. 5, where the lengths and integrity tests are identical except the minimum annulus barrier lengths when logged with CBL. See examples of the well barrier diagrams in **Error! Reference source not found.** below.



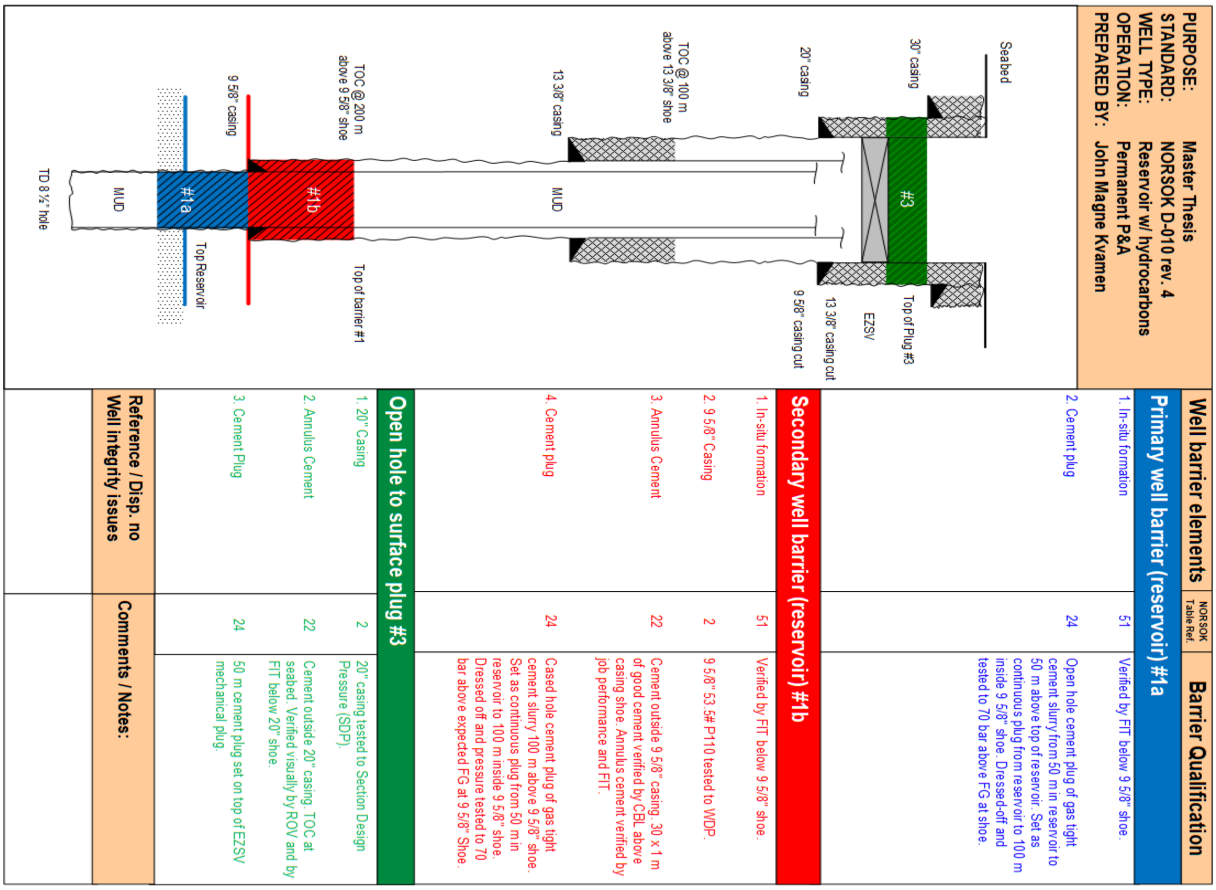


Figure 3.1: Minimum Well Barrier Requirements NORSOK D-010 rev. 5 and rev. 4 (based on Standard Norge 2021 and 2013)

3.2. NORSOK D-010 and OGUK Well Decommissioning Guidelines

NORSOK D-010 (2021) and OGUK Well Decommissioning Guidelines (2018) are built somehow in the same way and covers similar topics within well integrity and barrier principles for P&A operations. The two standards are overall very similar and in agreement in the big picture. Where they differ is in the detail level, for example in well integrity and barrier element acceptance criteria, as NORSOK D-010 being more detailed. It is also identified through the theory review that requirements such as pressure testing, tagging/weight testing, and barrier lengths are less strict in the OGUK guideline.

The well barrier EAC-tables in NORSOK D-010 gives supplementary information easily accessible and understood as opposed to in OGUK well decommissioning guidelines. There is at the moment no similar setup of EAC-tables in OGUK but rather use of one table with potential issues and possible measures and mitigations.

The following chapters in NORSOK D-010 counterpart with the OGUK standard well decommissioning guidelines, ref. Table 3.3:

Table 3.3: NORSOK D-010 (2021) and OGUK Well Decommissiong Guidelines (2018) Chapters

NORSOK D-010 rev. 5 (2021)	OGUK Well Decommissioning Guidelines (2018)
3 Terms and definitions	Glossary
5 General barrier principles	3 Permanent Barriers 4 Verification of a Permanent Barrier
10 Abandonment activities	3 Permanent Barriers 4 Verification of a Permanent Barrier
Annex C Well barrier elements acceptance tables	C Cement Barrier Placement

A detailed comparison of barrier materials, verification of same, and permanent plugging & abandonment requirements will be discussed in Table 3.4. It will cover the minimum requirements from both standards. It is recognized that the minimum requirements from the standards differ from the recommended requirements.

Table 3.4: Barrier Comparison of NORSOK D-010 (2021) and OGUK Well Decommissioning Guidelines (2018)

	NORSOK D-010 rev. 5 (2021)	**Oil & Gas UK Well Decommissioning Guidelines (2018)**	**Differences between standards**
Topic	**Minimum Requirement**		**Comments**
Permanent barrier perspective	Eternity.	Long-term integrity.	The two definitions are discussable, and no values are given for the barrier perspective. One can interpret this as having well integrity in the foreseeable future.
Barrier material	Portland cement is the natural barrier element, and any alternative barrier material shall undergo a verification process according to DNV RP-A203 Technology Qualification. Properties such it won't deteriorate over time and can withstand the wellbore environment in all foreseeable circumstances. Barrier material shall have better or as good sealing capabilities as the original cap rock. **Properties:** • **Long term integrity:** no deteriorating long-term trend. • **Permeability:** have permeability as low as the cap rock it replaces. • **Radial shrinkage:** low shrinkage is acceptable for barriers in open hole, while a long-term positive linear expansion is required for cased hole. • **Mechanical loads:** withstand all foreseeable loads in the future. For WBEs exposed to loads outside knowledge/expertise envelopes, FEA analysis should be performed with a 40% safety factor. • **Chemical stability:** withstand exposure to downhole chemicals without affecting integrity. • **Bonding to tubulars:** bond to any tubular. If bonding is not achievable, a compensating mechanism, such as expansion properties, shall be in place. • **Effect on tubular integrity:** not affect barrier material when in contact with tubulars or equipment.	Cement (Portland) is referred to as the accepted barrier material in the standard, but it is recognized that new barrier technologies are under development, and these shall undergo be qualified through the separate guideline Oil & Gas UK Guidelines for Qualification of Materials for the Abandonment of Wells. Properties such it won't deteriorate over time and can resist the wellbore environment for all foreseeable pressures and temperatures. The goal is to restore the cap rock. **Properties:** • **Long term integrity:** not deteriorate over time. • **Permeability:** low enough permeability such flow is prevented through. • **Radial shrinkage:** should be designed to minimise radial shrinkage. • **Mechanical loads:** characteristics suitable to withstand present and future loads. • **Chemical stability:** withstand exposure to downhole chemicals and foreseeable pressures and temperatures. • **Bonding to tubulars:** designed to maximize bonding to tubulars. • **Effect on tubular integrity:** not affect barrier material when in contact with tubulars or equipment.	Both standards recognize Portland cement as the accepted PP&A barrier material today but also see the need for new technologies. The standards refer to two different guidelines for technology qualification. Both of them will be discussed in Chapter 3.5. The two standards require the barrier material to withstand wellbore environment in all foreseeable circumstances. There is some variations between them, especially on the detail level, despite having the same ultimate goal. • **Long term integrity:** no difference. • **Permeability:** difference in the wording but same goal. • **Radial shrinkage:** NORSOK differentiate between shrinkage in open and cased hole with different criteria, while OGUK requires to minimise shrinkage. • **Mechanical loads:** NORSOK gives a more detailed and stricter requirement opposed to OGUK whereas being more general in their description. • **Chemical stability:** no difference. • **Bonding to tubulars:** NORSOK is more detailed opposite to OGUK. The end goals for both is to maximize bonding. • **Effect on tubular integrity:** no difference.

Barrier verification	**Pressure testing:** 70 bar above fracture pressure at barrier depth for intermediate casings and below, and 35 bar for surface casings and above. **Tagging/weight test:** in general, the barrier should be tagged to verify TOC, and load tested to verify hard cement. **Note:** verification shall be according to its respective EAC-table.	**Pressure testing:** minimum 35 bar (500 psi) above fracture pressure at barrier depth for all casings. **Tagging/weight test:** can be used as a combination of appropriate verification methods.	NORSOK has stricter barrier verification criteria than OGUK. NORSOK requires pressure test of 70 bar above fracture pressure for intermediate casings/liners and below, while OGUK requires 35 bar. Tagging/weight testing is required in NORSOK while in OGUK it may be a part of the verification method, i.e., no requirement to tag/weight test. Most of permanent barriers are placed in the intermediate casing/liner area or below.
PP&A of well with no hydrocarbons	**Hydrostatic pressure:** one barrier. **Over pressurized:** two barriers if there exist flow potential. One barrier if there is no potential for flow.	**Hydrostatic pressure:** one barrier. **Over pressurized:** two barriers.	Where the two standards differ is for an over pressurized zone with no flow potential. NORSOK D-010 has a minimum of 1 barrier, while OGUK requires minimum of two barriers. There is in addition mentioned in OGUK that a thorough risk assessment shall be performed to quantify the exact number of barriers. This is interpreted such if a risk assessment concludes having one barrier is sufficient, that is feasible.
*PP&A of well with hydrocarbons	**Hydrostatic pressure:** two barriers if zone got flow potential. One barrier if zone got no flow potential. **Over pressurized:** two barriers if zone got flow potential. One barrier if there is no potential for flow.	**Hydrostatic pressure:** two barriers. **Over pressurized:** two barriers. **Note:** barrier numbers are generally speaking, and a thorough risk assessment should be done on number of barriers.	In NORSOK D-010 is it differentiated between zones with flow potential and not, whereas in the case with no flow potential there is only required minimum one barrier, and two otherwise. In OGUK there is required two barriers regardless of flow potential. There is in addition mentioned in OGUK that a thorough risk assessment shall be performed to quantify the exact number of barriers. This is interpreted such if a risk assessment concludes having one barrier is sufficient, that is feasible.
PP&A of cased hole	**Cement plug length:** 50 m if set on a mechanical structure, or else 100 m. **Note:** when 30 m of annular cement barrier has been verified through logging, cement plug inside casing may be 30 m if set on a mechanical structure.	**Cement plug length:** 30 m either set on a mechanical structure or extended from open hole. ***The cement shall be of good quality.	NORSOK being stricter than OGUK regarding cased hole cement barrier length, but in the case where the annular cement has been verified through CBL/USIT bond log, the length requirement is the same.

PP&A of open hole	**Cement plug length:** 100 m where 50 m shall be above potential source of inflow. When transitioning between open and cased hole, it shall be 50 m above and below the casing shoe.	**Cement plug length:** 30 m where 15 m shall be above any potential source of inflow. When transitioning between open and cased hole, it shall be 15 m above and below the casing shoe.	NORSOK being stricter than OGUK for open hole cement barriers with a magnitude of above 3 times.
Annular barrier requirement	**Cement plug length:** general, 100 m. 200 m shall be used for the production casing above the reservoir. If qualified through logging it shall be 30 m of good cement.	**Cement plug length:** general, 30 m. 60 m shall be used for the production casing above the reservoir. ***The cement shall be of good quality.	NORSOK being stricter than OGUK for annular cement barriers with a magnitude of above 3 times. There is also opposing views on how to verify good annular cement, while in NORSOK it has to be verified through logging, while in OGUK it is accepted to use pressure or inflow test for barrier qualification purpose.
**Environmental plug	Shall install an environmental plug. **Length:** 50 m if set on a mechanical structure, or else 100 m.	May install an environmental plug. **Length:** no requirement specified.	There is a requirement to install an environmental plug in NORSOK D-010 while in OGUK there is an option to. In addition, OGUK does not specify any physical requirements of the plug.

* In NORSOK D-010 it is specified that it is possible to reduce number of barriers by one for zones with limited to zero flow potential if a thorough risk assessment is done yielding an acceptable risk level.

** The environmental plug is not a barrier.

*** Good cement is according to OGUK Decommissioning Guidelines (2018, p. 6) verified through pressure or inflow testing.

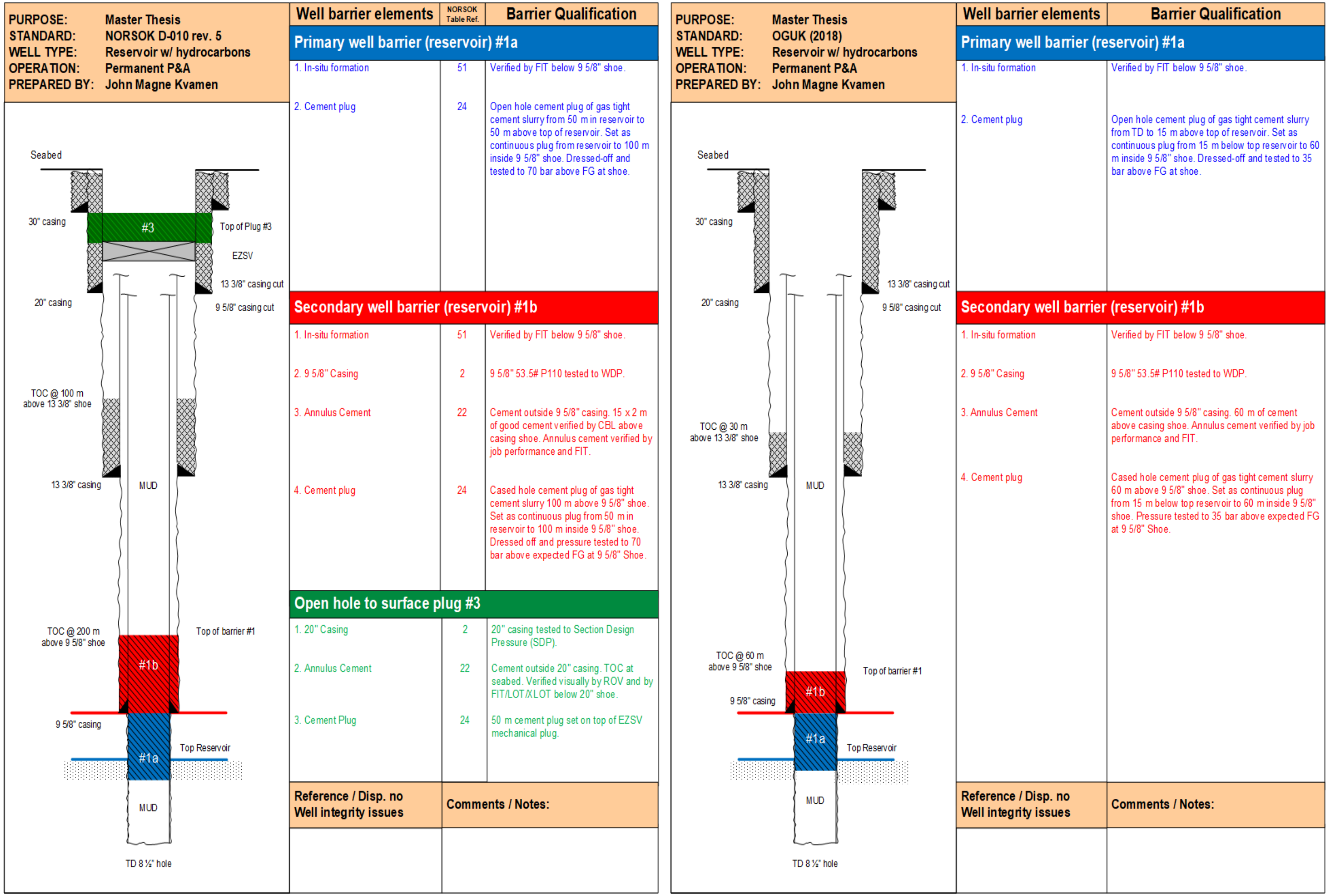


Figure 3.2: Minimum Well Barrier Requirements NORSOK D-010 and OGUK (based on Standard Norge 2021 and UKOOA 2018)

3.3. NORSOK D-010 and API Wellbore Plugging and Abandonment

NORSOK D-010 (2021) and API wellbore plugging and abandonment (2021) are two standards build similar to each other in the P&A-part, where the API standard is focusing on operating environment, barrier materials, installation techniques, and evaluation and verification criteria, which is also covered in NORSOK D-010. It is identified in the theory review that the two standards has similar approach in permanent plugging of wells, but it has also been recognized that the API standard is more focused on installation techniques and calculation of plug methods opposed to comprehensive barrier requirements and dimensions and numerical values for barrier plugs.

There is no similar descriptive barrier tables as "Annex C Well barrier elements acceptance tables" in the API standard. The following chapters in NORSOK D-010 counterpart with API wellbore plugging and abandonment, ref. Table 3.5:

Table 3.5: NORSOK D-010 (2021) and API Wellbore Plugging and Abandonment (2021) Chapters

NORSOK D-010 rev. 5 (2021)	API Wellbore Plugging and Abandonment (2021)
3 Terms and definitions	3 Terms and Definitions, Symbols, and Abbreviations
5 General barrier principles	5 Material Consideration for Barriers 6 Installation
10 Abandonment activities	4 Applications and Operating Environment 5 Material Consideration for Barriers
Annex C Well barrier elements acceptance tables	-

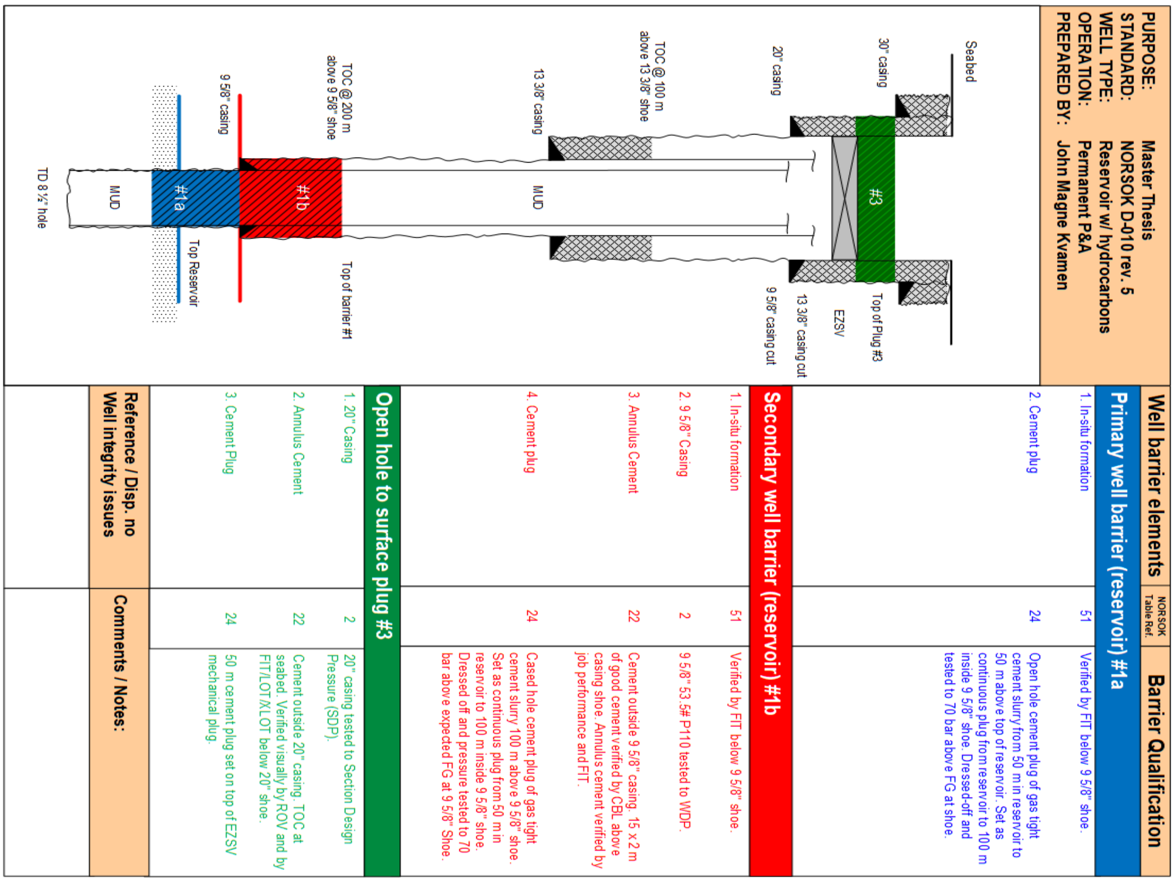
A detailed comparison of barrier materials, verification of same, and PP&A requirements will be discussed in Table 3.6. It will cover the minimum requirements from both standards. See Figure 3.3 for a well barrier diagram comparison between them.

Table 3.6: Barrier Comparison of NORSOK D-010 (2021) and API Wellbore Plugging and Abandonment (2021)

	NORSOK D-010 rev. 5 (2021)	API Wellbore Plugging and Abandonment (2021)	Differences between standards
Topic	**Minimum Requirement**		**Comments**
Permanent barrier perspective	Eternity.	Planned service life.	Same as for OGUK, no further description or distinct value is given for the perspective but rather both definitions is interpreted as the barrier shall never fail.
Barrier material	Portland cement is the natural barrier element, and any alternative barrier material shall undergo a verification process according to DNV RP-A203 Technology Qualification. Properties such it won't deteriorate over time and can withstand the wellbore environment in all foreseeable circumstances. Barrier material shall have better or as good sealing capabilities as the original cap rock. **Properties:** • **Long term integrity:** no deteriorating long-term trend. • **Permeability:** have permeability as low as the cap rock it replaces. • **Radial shrinkage:** low shrinkage is acceptable for barriers in open hole, while a long-term positive linear expansion is required for cased hole. • **Mechanical loads:** withstand all foreseeable loads in the future. For WBEs exposed to loads outside knowledge/expertise envelopes, FEA analysis should be performed with a 40% safety factor. • **Chemical stability:** withstand exposure to downhole chemicals without affecting integrity. • **Bonding to tubulars:** bond to any tubular. If bonding is not achievable, a compensating mechanism, such as expansion properties, shall be in place. • **Effect on tubular integrity:** not affect barrier material when in contact with tubulars or equipment.	Portland cement is the reference point for the API standard as this is the commonly used one and considered the most accepted PP&A material, whereas it is said that the sealing material shall have a permeability as low as Portland cement, or same as the cap rock it replaces. API does not mention any alternative material, either disqualifies alternative material other than Portland cement. The barrier material shall have properties that has no deteriorating sealing abilities over time and is appropriate for the loads in the set environment. End goal of API is to restore the cap rock. **Properties:** • **Long term integrity:** long durability. • **Permeability:** equal or lower than Portland cement, or the cap rock it replaces. • **Radial shrinkage:** not degrade over time. • **Mechanical loads:** withstand the wellbore environment. • **Chemical stability:** withstand common wellbore chemicals. • **Bonding to tubulars:** design of barrier shall take into consideration potential flow paths due to degradation of tubulars. • **Effect on tubular integrity:** not described.	The standards refer to Portland cement as being the primary barrier material used as of today, but NORSOK details a specific qualification plan for alternative materials according to DNV, while API does not refer to any qualification plan or disqualifies alternative materials. As long as the barrier material holds the mentioned properties as mentioned by API, the material should be good. The two standards require barrier materials shall withstand wellbore environment in all foreseeable matters. There exist a difference in the detail level between them, where NORSOK give an in-depth description and requirement, while API has a general approach. • **Long term integrity:** similar requirement but NORSOK detailing how a long term integrity is achieved. • **Permeability:** NORSOK require a permeability as low as the cap rock it replaces (for shale 10^{-3}-10^{-5} mD) while API sets Portland cement as the minimum (10^{-2} mD). • **Radial shrinkage:** NORSOK differentiate between open and cased hole, specifying an expansion is required in cased hole, while API says degradation over time shall not happen. • **Mechanical loads:** NORSOK gives a more detailed and stricter

			requirement opposed to API being more general in their description. • **Chemical stability:** practically no difference. • **Bonding to tubulars:** NORSOK is stricter and more descriptive in requirements while API says that potential flow paths should be considered in the barrier design. • **Effect on tubular integrity:** NORSOK requires that the barrier material will not be affected if in contact with equipment, while API has not included it in their standard.
Barrier verification	**Pressure testing:** 70 bar above fracture pressure at barrier depth for intermediate casings and below, and 35 bar for surface casings and above. **Tagging/weight test:** In general, the barrier should be tagged to verify TOC, and load tested to verify hard cement. **Note:** Verification shall be according to its respective EAC-table.	**Pressure testing:** shall be performed to verify the barrier integrity for annular and cased hole cement barriers. No values given in the standard. **Tagging/weight test:** tagging cement and applying weight to verify for cased and open hole barriers. No values given in the standard.	Both standards have the same view of pressure testing and tagging/weight testing, but NORSOK gives numerical values while API does not.
PP&A of well with no hydrocarbons	**Hydrostatic pressure:** one barrier. **Over pressurized:** two barriers if there exist flow potential. One barrier if there is no potential for flow.	**Hydrostatic pressure:** are not described as potential flow zones. **Over pressurized:** water-bearing zones, either natural or induced, shall be isolated.	NORSOK gives strict minimum barrier criteria for the two scenarios while API does not cover hydrostatically pressured zones without hydrocarbons. For over pressured zones with no hydrocarbons, API mentions water-bearing zones, but no minimum number of barriers is given.
PP&A of well with hydrocarbons	**Hydrostatic pressure:** two barriers if zone got flow potential. One barrier if zone got no flow potential. **Over pressurized:** two barriers if zone got flow potential. One barrier if there is no potential for flow.	**Hydrostatic- and over pressured:** hydrocarbon bearing zones shall be isolated.	NORSOK gives detailed minimum criteria for barriers while API has a general approach and state that the zones shall be isolated, but no minimum numbers are given.
PP&A of cased hole	**Cement plug length:** 50 m if set on a mechanical structure, or else 100 m. **Note:** when 30 m of annular cement barrier has been verified through logging, cement plug inside casing may be 30 m if set on a mechanical structure.	**Cement plug length:** no length requirements or details are given for cased hole barriers in API.	
PP&A of open hole	**Cement plug length:** 100 m where 50 m shall be above potential source of inflow.	**Cement plug length:** no length requirements or details are given for open hole barriers in API.	

	When transitioning between open and cased hole, it shall be 50 m above and below the casing shoe.		
Annular barrier requirement	**Cement plug length:** general, 100 m. 200 m shall be used for the production casing above the reservoir. If qualified through logging it shall be 30 m of good cement.	**Cement plug length:** no length requirement are given for annular barriers in API. **Note:** an annular cement barrier shall initially be qualified through cement evaluation logs and pressure testing.	
Environmental plug	Shall install an environmental plug. **Length:** 50 m if set on a mechanical structure, or else 100 m.	Not mentioned in API.	NORSOK requires an environmental plug while API does not mention it in their standard.



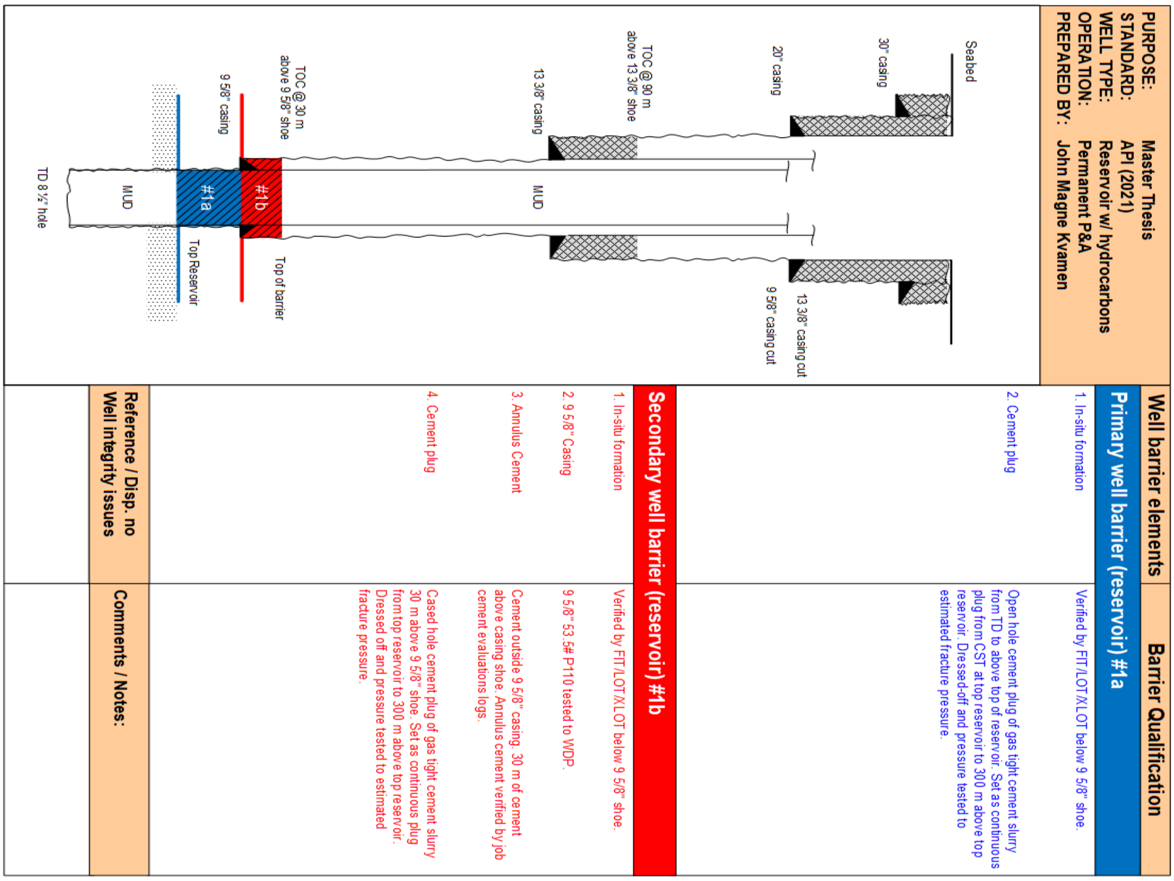


Figure 3.3: Minimum Well Barrier Requirements NORSOK D-010 and API (based on Standard Norge 2021 and API 2021)

3.4. NORSOK D-010 and DNV Risk based Abandonment of Wells

NORSOK D-010 (2021) and DNV Risk based abandonment of wells (2020) is two similar well integrity standards within PP&A, where the main distinction between them are DNV comprise a greater risk-based approach opposed to NORSOK. There lacks general description in DNV of barrier elements and instead goes in detail into permanent abandonment criteria.

There is no similar descriptive barrier tables as “Annex C Well barrier elements acceptance tables” in the DNV standard. The following chapter in NORSOK D-010 counterpart with DNV Risk based Abandonment of Wells, ref. Table 3.7:

Table 3.7: NORSOK D-010 (2021) and DNV Risk based abandonment of wells (2020)

NORSOK D-010 rev. 5 (2021)	DNV Risk based abandonment of wells (2020)
3 Terms and definitions	1.6 Definitions and abbreviations
5 General barrier principles	Section 2 System description Section 3 Risk assessment process for well abandonment design
10 Abandonment activities	Section 3 Risk assessment process for well abandonment design
Annex C Well barrier elements acceptance tables	-

A detailed comparison of barrier materials, verification of same, and permanent plugging & abandonment requirements will be discussed in Table 3.8. It will cover the minimum requirements from both standards.

Table 3.8: Barrier Comparison of NORSOK D-010 (2021) and DNV Risk based abandonment of wells (2020)

	NORSOK D-010 rev. 5 (2021)	**DNV Risk based abandonment of wells (2020)**	**Differences between standards**
Topic	**Minimum Requirement**		**Comments**
Permanent barrier perspective	Eternity.	Long-term integrity and reliable.	The two definitions are discussable, and no values are given for the barrier perspective. One can interpret this as having well integrity in the foreseeable future.
Barrier material	Portland cement is the natural barrier element, and any alternative barrier material shall undergo a verification process according to DNV RP-A203 Technology Qualification. Properties such it won't deteriorate over time and can withstand the wellbore environment in all foreseeable circumstances. Barrier material shall have better or as good sealing capabilities as the original cap rock. **Properties:** • **Long term integrity:** no deteriorating long-term trend. • **Permeability:** have permeability as low as the cap rock it replaces. • **Radial shrinkage:** low shrinkage is acceptable for barriers in open hole, while a long-term positive linear expansion is required for cased hole. • **Mechanical loads:** withstand all foreseeable loads in the future. For WBEs exposed to loads outside knowledge/expertise envelopes, FEA analysis should be performed with a 40% safety factor. • **Chemical stability:** withstand exposure to downhole chemicals without affecting integrity. • **Bonding to tubulars:** bond to any tubular. If bonding is not achievable, a compensating mechanism, such as expansion properties, shall be in place. • **Effect on tubular integrity:** not affect barrier material when in contact with tubulars or equipment.	No reference to Cement, or Portland, is referred to as the accepted barrier material in the standard. The goal for the standard is to determine performance and functional requirements for PP&A materials to further allow alternative materials to be qualified upon that. A well barrier may consist of anything as long as it provides the required well integrity characteristics. Sensitivity studies should be performed to assess the risk of degradation. A barrier shall be placed in an impermeable interval, meaning the material itself shall also be impermeable. **Properties:** • **Long term integrity:** remain reliable and robust for a long period of time. • **Permeability:** low enough permeability such flow is prevented through. • **Radial shrinkage:** minimize such flow around is not possible. • **Mechanical loads:** designed to withstand all wellbore environment loads. • **Chemical stability:** able to withstand any sensibly foreseeable chemical process. • **Bonding to tubulars:** maximize such flow around is not possible. • **Effect on tubular integrity:** shall not affect well integrity such flow through barrier happens.	While NORSOK specify Portland cement as the natural barrier, DNV generalizes it as a barrier. Where DNV recognize the need for alternative materials more than NORSOK, they both refer to the qualification process by DNV Technology Qualification. Also, DNV states that a PP&A material can consist of anything as long as it provides well integrity. Main variation between the standards are that NORSOK has a stricter approach while DNV pinpoints the need for technology change in the PP&A-phase. • **Long term integrity:** no difference. • **Permeability:** difference in the wording but same goal. • **Radial shrinkage:** NORSOK differentiate between shrinkage in open and cased hole, while DNV requires to minimize shrinkage such flow cannot pass. • **Mechanical loads:** NORSOK is detailed while DNV is more general in their description. • **Chemical stability:** DNV describe it in a more risk-based way opposed to NORSOK. • **Bonding to tubulars:** Same goal but NORSOK being more detailed. • **Effect on tubular integrity:** no difference.

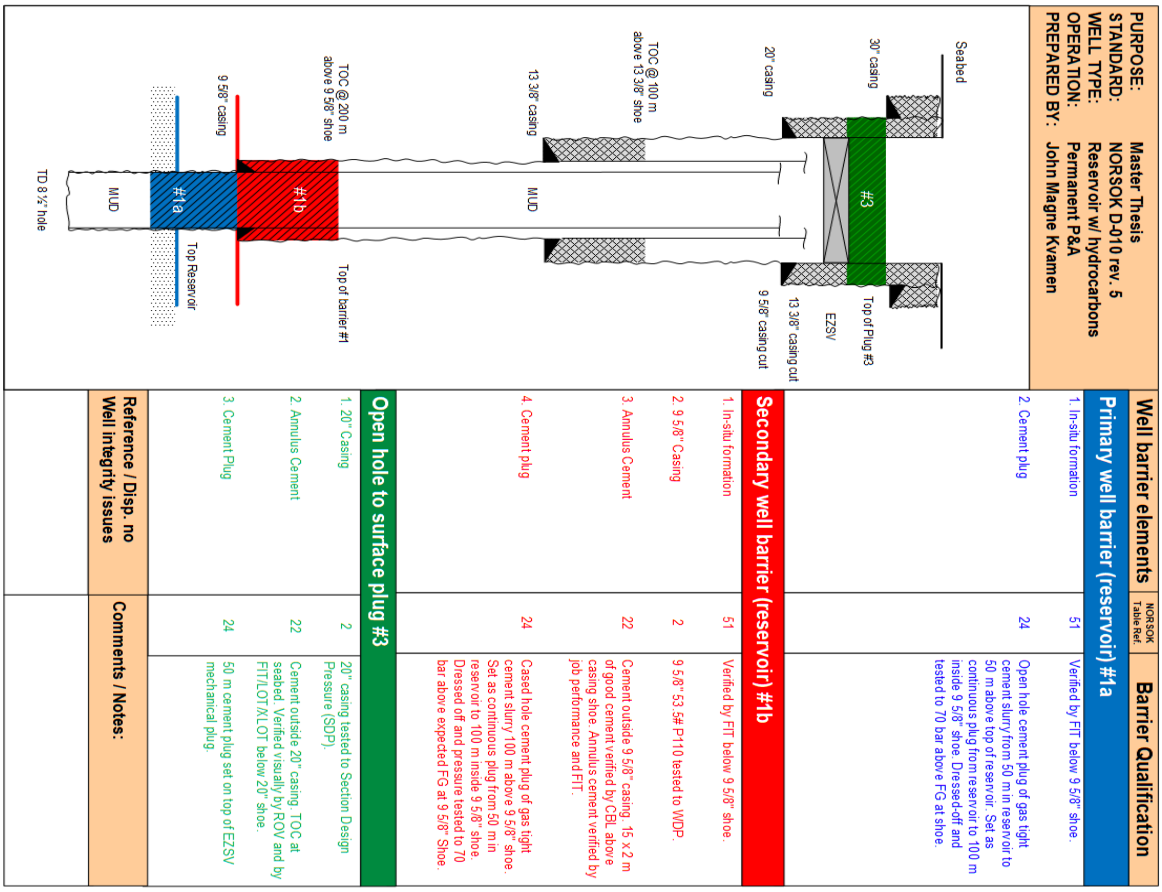
Barrier verification	**Pressure testing:** 70 bar above fracture pressure at barrier depth for intermediate casings and below, and 35 bar for surface casings and above. **Tagging/weight test:** In general, the barrier should be tagged to verify TOC, and load tested to verify hard cement. **Note:** Verification shall be according to its respective EAC-table.	**Pressure testing and tagging:** not specified how to verify a barriers integrity but rather recommends using a risk-based approach to determine loss of containment based on the established acceptance criteria.	While NORSOK gives verification criteria for permanent barriers, DNV has a risk-based approach where the verification method is up to the operator and shall be based on its acceptance criteria.
PP&A of well with no hydrocarbons	**Hydrostatic pressure:** one barrier. **Over pressurized:** two barriers if there exist flow potential. One barrier if there is no potential for flow.	**Hydrostatic pressure:** N/A **Over pressurized:** N/A **Hydrostatic and over pressured:** zones not containing hydrocarbons, or pressurized water-bearing zones, are not covered in DNV's standard.	The NORSOK standard covers barrier requirements for wells not containing hydrocarbons or is water-bearing (pressurized) but DNV does not.
PP&A of well with hydrocarbons	**Hydrostatic pressure:** Two barriers if zone got flow potential. One barrier if zone got no flow potential. **Over pressurized:** Two barriers if zone got flow potential. One barrier if there is no potential for flow.	**Hydrostatic pressure:** Zero to one barrier if zone has no flow potential. For a zone with moderate flow potential, one to two barriers. For a zone with significant flow potential, two barriers. **Over pressurized:** For zone with moderate flow potential, one to two barriers. For zones with significant flow potential, two barriers.	DNV has not the same approach to plugging of wells with hydrocarbons as NORSOK and instead categorizes purely on potential for flow. By nature, an over pressurized zone has more flow potential than a hydrostatic one, therefore it is possible to categorize them somehow on pressure, but a thorough risk-assessment has to be in place regardless.
PP&A of cased hole	**Cement plug length:** 50 m if set on a mechanical structure, or else 100 m. **Note:** When 30 m of annular cement barrier has been verified through logging, cement plug inside casing may be 30 m if set on a mechanical structure.	**Cement plug length:** a risk based approach with regards to consequence and likelihood should be performed, referring to the risk matrix (DNV 2020, figure 4-3). The barrier length shall be sufficient enough to cease any potential flow through. For example, for annulus cement it is given, if good cement is proved, that cement length may be > 50 m. Quantitative models should be used in the risk management strategy when assessing the required barrier length.	Although NORSOK giving definite length requirements, DNV gives some values based on the risk level but ultimately says a risk-based approach should be followed.
PP&A of open hole	**Cement plug length:** 100 m where 50 m shall be above potential source of inflow. When transitioning between open and cased hole, it shall be 50 m above and below the casing shoe.		
Annular barrier requirement	**Cement plug length:** General, 100 m. 200 m shall be used for the production casing above the reservoir. If qualified through logging it shall be 30 m of good cement.		
Environmental plug	Shall install an environmental plug. **Length:** 50 m if set on a mechanical structure, or else 100 m.	An environmental plug should be set. **Length:** not described.	DNV gives a recommendation to set an environmental plug while it is a requirement in NORSOK.

Based on a risk assessment it is possible to set numerical values for the pressure testing and cement lengths based on minimum hydraulic isolation lengths. Ashena R. et al. (2014, p. 3) assessed cement lengths using cement bond log evaluations based on field tests. A pre-defined cement interval is required to make sure it has hydraulic isolation. The minimum interval required varies based on tubular size (Ashena R. et al. 2014, p. 16). The paper covers tubular sizes from 4 ½” to 9 5/8”, ref. Figure 3.4.

Incorporating the minimum required values from the field study performed by Ashena R. et al (2014), assuming the wellbore has been drilled in a familiar area with a good track record, the minimum barrier requirements in the well integrity standard from DNV (2020) can be concluded and is shown in **Error! Reference source not found.**.

Pipe				CBL Value		
OD	Wt.	(μs) TT	Free Pipe (CBL (mv))	BI=100%	BI=60%	Min. Hydraulic Isolation Interval (ft)
4 1/2″	9.5	254	81	0/2	2/3	5 Feet
	11/6			0/6	4/6	
	5/13			1/0	7/0	
5″	15	258	76	0/9	5/5	5 Feet
	18			2/2	10	
	21			3/6	15	
5 1/2″	15/5	269	72	0/7	4/8	6 Feet
	17			1	6	
	20			2/1	9	
	23			3/5	13	
7″	23	289	62 mv	1	5/5	11 Feet
	26			1/7	7/5	
	29			2/4	9/3	
	32			3/3	13	
	35			4	14	
	38			5	15	
	40			6	17	
7 5/8″	26/4	302	59 mv	1/1	5/5	12 Feet
	29/7			1/8	7/5	
	33/7			2/6	10/0	
	39			3/5	13/0	
9 5/8 ″	40	332	51 mv	1/8	6/8	15 Feet
	43/5			2/2	8/5	
	47			2/7	9	
	53/.5			4	12	

Figure 3.4: Minimum Hydarulic Isolation Intervals Determined by CBL (Ashena R. et al 2014, Appendix A)



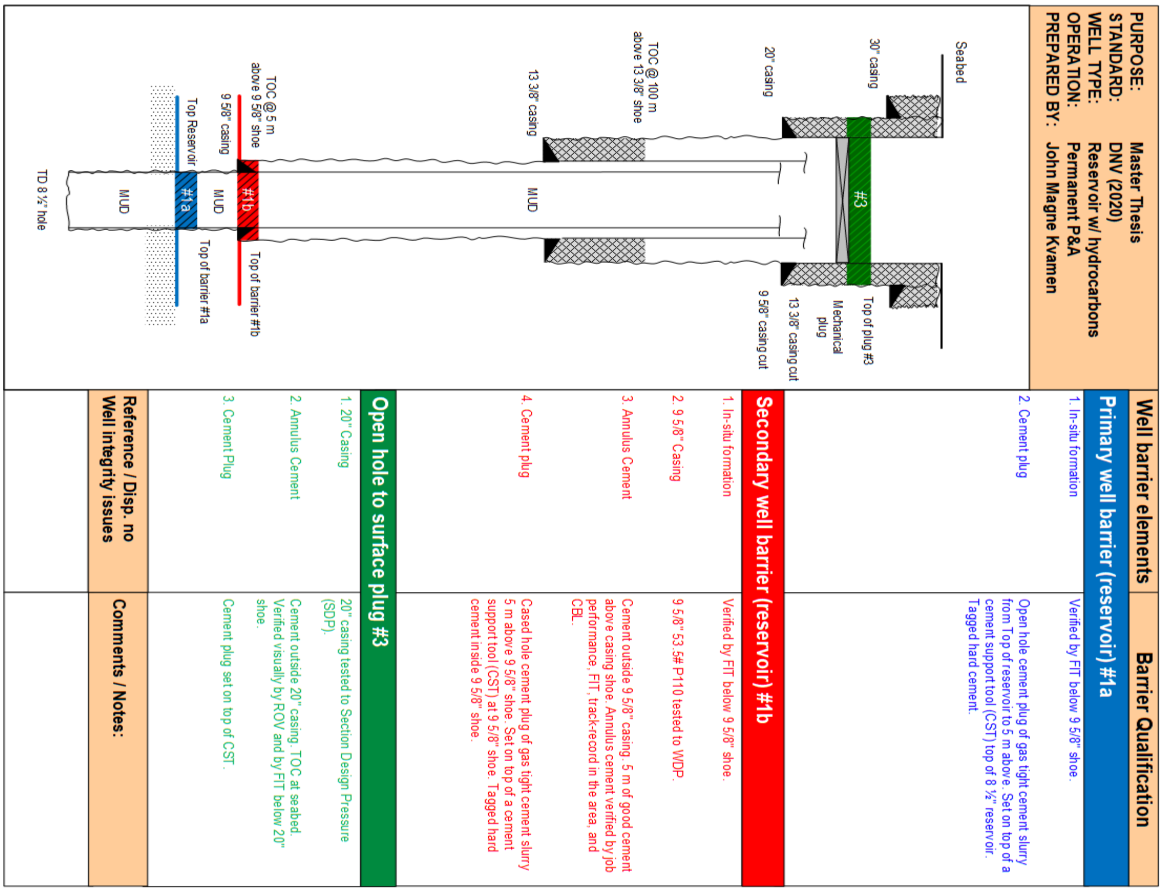


Figure 3.5: Minimum Well Barrier Requirements NORSOK D-010 and DNV (based on Standard Norge 2021 and DNV 2020)

PART II

CEMENTITIOUS MATERIALS

4. Plug & Abandonment Materials in Oil & Gas

Chapter 4 will cover description of the commonly used barrier material Portland cement, in addition to elaborate on alternative barrier materials either under development or qualified, especially focusing on rock-based geopolymer cement. Each barrier material's failure modes, advantages, and disadvantages, and if relevant, their environmental footprint, will be discussed.

The focus being will be on whether geopolymer-based cement is acceptable to be used as a barrier element in PP&A operations.

4.1. Portland G-Cement

Minimal changes in P&A materials has happened in the last few decades, where the most significant changes has been on additives added to Portland cement to strengthen some of its properties, such as expansion and gas-tight properties (Rios R. and Ars F. 2021, p. 3). Reasoning for Portland cement being the preferred choice is due to it satisfying parameters similar to a cap rock. It has properties such as a low bulk porosity and permeability and is highly durable when the cement length is sufficiently long. Normal Portland cement does not withstand corrosive environments and high temperatures well, in addition to losing its hydrostatic pressure column when it sets, which can substantially increase the differential pressure on the barrier if the cement length is too long relative to the wellbore.

Through a calcination and a hydration process, the chemical compound Portland cement is created (Salehi S. et al. 2017, pp. 2-3). By first reacting calcium with silicon dioxide in a calcination system followed by a water-cement clinker phase, where the compounds reacts together and forms Portland cement slurry.

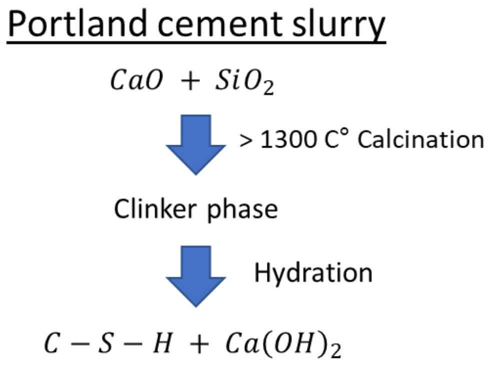


Figure 4.1: Portland Cement Chemical Process (based on Salehi S. et al. 2017, figure 1)

Producing one MT of cement yields emissions of 1.00 MT of CO_2 (Davidovits J. 2013, p. 6). It directly pollute 1.00 MT through the chemical calcination reaction, as seen below, in addition to 0.020 MT of CO_2 during the crushing process.

$$5CaCO_3 + 2SiO_2 \rightarrow (3CaO, SiO_2)(2CaO, SiO_2) + 5CO_2$$

$$\downarrow$$

$$1.00\ MT\ Portland\ cement = 1.00\ MT\ CO_2$$

There is few possibilities to reduce the CO2-emission from production of Portland cement, for example by using fly ash (Davidovits J. 2013, p. 6). Fly ash in Portland cement may decrease CO_2 pollution with 10 to 15 percentages.

A more important aspect for Portland cement is its properties and what such cement type can withstand. Properties for a Portland cement slurry with no performance additives added, which is the standard for permanent barriers, are given in Table 4.1. For reference, there is used a cement slurry between 1,892 and 1,950 kg/m^3 for the values below.

Table 4.1: Portland Cement Properties (based on Kamali M. et al 2021 and Ogienagbon AA. et al. 2022)

Property	Units	Value
[1]Permeability	µD	10
[2]Modulus of elasticity	GPa (psi)	8.1 to 8.8 (1,175,000-1,276,000)
[3]Poisson ratio	-	0.09 to 0.16
[4]Cohesion	MPa (psi)	7.0 to 13.6 (1,015-1,973)
[5]Internal friction angle	°	0.50 to 0.26
[6]Tensile strength at t = 1 day	MPa (psi)	~ 2.25 (± 326,335)
[6]Tensile strength at t = 5 days		~ 2.20 (± 319,080)
[6]Tensile strength at t = 7 days		~ 2.10 (± 304,580)
[6]Tensile strength at t = 28 days		~ 1.30 (± 188,550)
[7]Pumpability	Minutes	132 in atm. and 96 pressurized
[8]Thermal conductivity at 30°C, 50°C, 70°C, 100°C, 130°C, 150°C	$W/(m \times K)$	0.84, 0.85, 0.82, 0.80, 0.69, N/A
[9]Fluid-loss	ml/30 min	821
[10]Shear bond strength in clean pipe	MPa	± 0.6
[10]Shear bond strength in rusty pipe	MPa	± 0.7
[10]Hydraulic bond strength in clean pipe	Psi	± 200
[10]Hydraulic bond strength in rusty pipe	Psi	± 200

[1]Reference Table 2.1 in Chapter 2. Literature Study

[2]Measured at 30°C and 90°C; 172 bar (Ogienagbon AA. et al. 2022, p. 7)

[3]Measured at 30°C and 90°C; 172 bar (Ogienagbon AA. et al. 2022, p. 8)

[4-5]Measured at 30°C and 90°C; 172 bar (Ogienagbon AA. et al. 2022, p. 14)

[6,7]Measured 1, 5, 7, and 28 days after curing; density of 1.95 sg and in 90°C /170 bar (Kamali M. et al. 2021, p. 4)

[8]Measured in 1.90 sg and samples cured in ambient pressure and 70°C for 7 days (Wiktorski E. et al. pp. 690-691)

[9]Measured in 138 bar and 70°C, value extrapolated from a 2 min experiment (Khalifeh M. et al. 2018, p. 4)

[10]Samples cured at 90°C (Kamali M. et al. 2022, pp. 6-8)

Pure Portland cement has three widely known failure modes; micro annulus, cement cracks, and leakage through bulk cement (Rios R. and Ars F. 2021, pp. 3-4). The failure modes are caused by for example cement shrinkage during curing, poor bonding with the tubular, cement failure under stress, which in turn affects the well integrity and decrease the 'eternity' perspective of a PP&A barrier. In addition to the shortcomings mentioned above, Portland cement also experience low brittleness and ductility, poor durability in erosive environments and increasing temperatures (Kamali M. et al. 2021, p. 2). In the table below, a summary of the advantages and disadvantages for Portland cement is given, ref. Table 4.2.

Table 4.2: Summary of Advantages and Disadvantages for Portland Cement

Ordinary Portland Cement Advantages and Disadvantages	
Advantages	**Disadvantages**
• Similar properties to the cap rock	• Shrinks after setting
• Low bulk porosity and permeability	• Loses its strength over time
• Highly durable when length is sufficient	• Degrades in corrosive environments
• Cheap and easily available	• Loses hydrostatic column when setting
• Has a high initially tensile strength	• Micro-annuli leakages
• Widely used and acknowledged	• Low brittleness and ductility
	• Low durability in erosive environments
	• Decreasing durability in increasing temperatures
	• High fluid-loss
	• Low shear bond strength
	• Low hydraulic bonding

4.2. Expandable Cement

As described in the earlier chapters, shrinkage of normal Portland cement is a concern with regards to the barriers hydraulic bond strength; whether the barrier will function as intended. It is a widely known weak spot of Portland cement which has been mitigated against in the last few years by adding agents to counteract shrinkage and instead make the cement expand (Ogienagbon AA. et al. 2022, p. 3). By using agents like CaO, MgO, saturated aggregates, and superabsorbent polymers in Portland cement, the shrinking properties will decrease due the micro cracks self-heals by themself, and bonding may maintain as intended.

Expandable cement goes through the same calcination and hydration process as Portland cement, and only posess agents to give it expandable properties relative to its original state, i.e., there is no environmental improvement but rather an advancement in sealing properties.

Full-scale tests has been performed using expandable and Portland cement by Aas B. et al. (2016) investigating the annular sealing capabilities of the two cement types when the tubing was left in hole. By performing pressure tests with seawater, it was quantified pressure drop and leakage rate over different increments in the annuli between 9 5/8” casing and 7” tubing, both containing control lines left in annulus and no control lines (Aas B. et al. 2016, pp. 2).

From Figure 4.2 and Figure 4.3, respectively of Portland and expandable cement, it looks like perfect cement displacement where one cannot see any annuli in the circumference, low-side, or around the control cables. By performing the pressure tests it is possible to quantify any micro-annuli that may exist, which is not visible from the pictures. In Table 4.3 and Table 4.4 one can see the induced pressures for the different tests performed, leakage rate, and at what pressure the leakage occurs.

Figure 4.2: Portland Cement Cut, No Control Lines (left) and Control Lines (right) (Aas B. et al. 2016, figure 9)

Figure 4.3: Expandable Cement Cut, No Control Lines (left) and Control Lines (right) (Aas B. et al. 2016, figure 11)

The experimental setup of the tests with Portland and expandable cement are shown in Figure 4.4 and Figure 4.5. Pressure values were recorded at contrasting places in the casing and leakage points and rates were documented. Based on pressures and leakage rates, the micro-annulus were calculated.

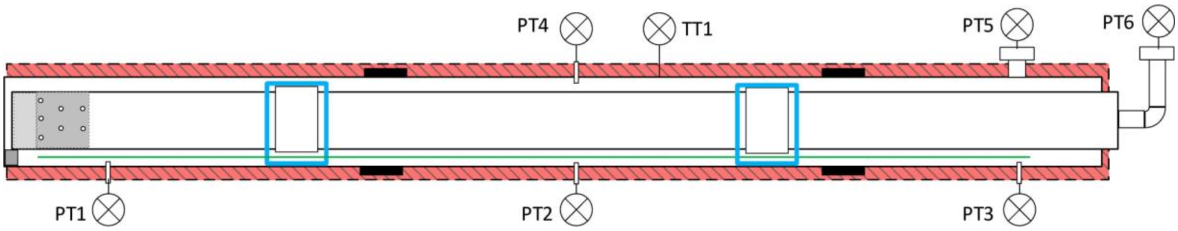


Figure 4.4: Experimental Setup of Portland Cement (Aas B. et al. 2016, figure 4)

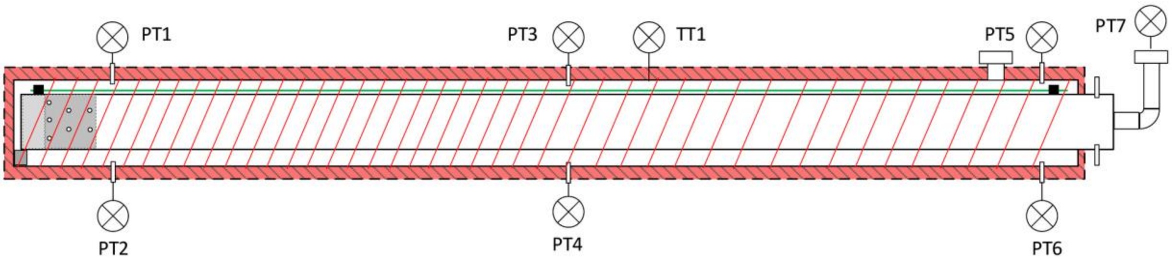


Figure 4.5: Experimental Setup of Expandable Cement (Aas B. et al. 2016, figure 7)

Difference in Table 4.3 and Table 4.4 proves that expandable cement provide better sealing capabilities opposed to conventional Portland cement, where the expandable cement has a lower calculated micro-annulus. It was also observed permanent micro-annuli in the Portland cement, which may be due to the shrinkage of normal Portland cement (Aas B. et al. 2016, p. 11). Considering the expanding forces in the expandable cement, it pushed against the casing wall, and it was needed a substantial differential pressure in order to create a micro-annuli.

Table 4.3: Leakage Rate and Micro-annuli for Portland Cement (Aas B. et al. 2016, table 2)

Pressure PT1	Pressure PT1-PT4	Leakage point	Leakage	Calculated microannulus	δR induced casing	δR induced cement
(bar)	(bar)		(ml/min)	(μm)	(μm)	(μm)
54	0.5	PT3:	14	65	28	8
93	2.5	PT3:	95		48	14
56	3.5	PT3:	16	56	29	8
		PT2:	40			
94	4.5	PT3:	43		48	14
		PT2:	93			

Table 4.4: Leakage Rate and Micro-annuli for Expandable Cement (Aas B. et al. 2016, table 3)

Pressure PT3	Pressure PT3 - PT6	Leakage	δR induced casing	δR induced cement	Calculated microannulus
(bar)	(bar)	(ml/min)	(μm)	(μm)	(μm)
125	48	98	44	15	22
126	48	94	44	15	22
127	49	92	45	15	22
96	50	49	32	11	18
95	51	48	31	10	17
66	47	23	19	6	14
65	44	23	19	6	14
42	30	13	9	3	13
42	30	13	9	3	13

It is important to note that the Portland cement-test used three casing lengths, i.e., 36 m of casing opposite to the expandable cement-test using one casing length, i.e., 12 m of casing (Aas B. et al. 2016, pp. 3-4). It should also be noted that the two different aging tests were cured for eight to nine days before the pressure testing commenced (Aas B. et al. 2016, p. 7). If curing had happened for a longer period of time, it could have advantaged the expandable cement more due to more potential shrinkage of normal Portland cement.

The potential micro-annuli during pressure testing may be permanent ones or induced from the pressure testing itself (Aas B. et al. 2016, p. 11). It is likely that the induced micro-annuli is local and non-uniform, and by having a longer cement plug the leakage rate will go down to practical zero.

Service companies offering commercial expandable cement in the oil & gas industry in Norway today are Baker Hughes (EnsurSet™), Halliburton (ExpandaCem™), and Schlumberger (FlexSEAL™).

4.3. Rock-based Geopolymer

The use of geopolymer-based cement as a barrier element in the oil & gas industry has been a topic the last decade but due to a technical complex testing and identification of potential failure modes and verifying of its use, it has still never been used as a barrier element for oil and/or gas wells.

Geopolymers, also known by inorganic polymers, is one category of cementitious materials and was first introduced in 1975 by Joseph Davidovits (Khalifeh M. et al. 2019, pp. 352-353). The inorganic polymers can be based upon different mineral resources such as fly-ash, rock, metakaolin, silica, and calcium. Common for the different mineral resources used, they constitute of long chemical structures repeating themselves forming tetrahedral aluminosilicate materials, which itself is the inorganic polymers. It is focused on use of rock-based geopolymers in this thesis, that meaning every reference to geopolymer cement is rock-based.

In order to produce rock-based geopolymer cement, the formed tetrahedral aluminosilicate materials has to be mixed together with a hardener (Khalifeh M. et al. 2019, p. 353). The hardener constituting of a combination of two solutions; alkali solution and alkali-silicate solution. It undergoes three distinct processes when the hardener is added; firstly dissolution, secondly orientation/transportation, lastly geopolymerization/polycondensation. The process for each of the distinct processes are described below, ref. Figure 4.6.

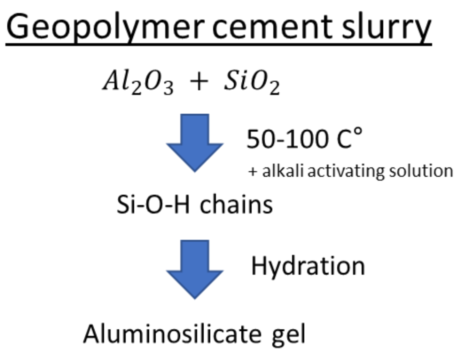


Figure 4.6: Geopolymer Cement Chemical Process (based on Salehi S. et al. 2017, figure 1)

Dissolution, a chemical process where the OH^- ions that is present in the hardener reacts with aluminosilicate particles and gets dissolved, followed by breaking Si-O and Al-O bonds and shaping silanol-groups, namely Si-O-H species.

Orientation/transportation, due to dissolution process described above, the ions and particles orientates and accumulate to increase the contact surface for silanol-groups and produces the molecule oligomers.

Geopolymerization/polycondensation, the newly produced oligomers connects with other oligomer molecules to build 3D-aluminosilicate chains, namely geopolymers, ref. Figure 4.7.

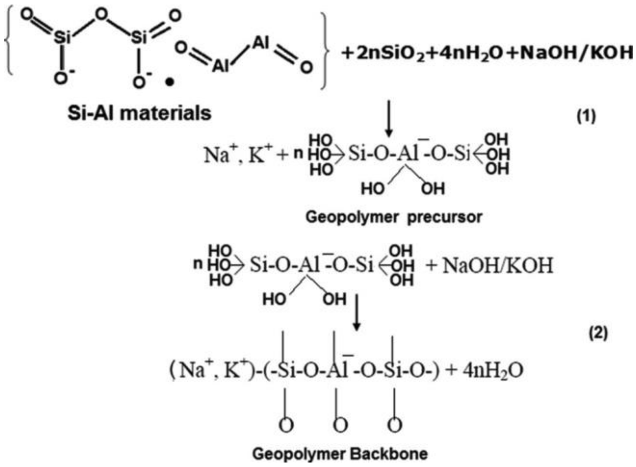


Figure 4.7: Geopolymer Chemical Process (Singh N. B. et al. 2020, scheme 1)

Producing one MT of geopolymer rock-based cement depends on where the by-product fly ash or blast furnace slag (BFS) derives from; whether as a waste material in industrial production or manufactured. Valid from Table 4.5, the reduction in energy consumption is more than one third while reduction in CO_2-emission varies from 70 to 80 percentages based on where the by-product derives from (Davidovits J. 2013, p. 7).

Table 4.5: Energy Consumption of Cements (based on Davidovits J. 2013, p. 7)

Energy Required	**Calcination [MJ/MT]**	**Crushing [MJ/MT]**	**Silicate [MJ/MT]**	**Total [MJ/MT]**	**Energy Increase/Reduction**
Portland Cement (default)	4,270	430	-	4,700	0%
Geopolymer Cement (BFS waste material)	1,200	390	375	1,965	- 59%
Geopolymer Cement (BFS manufacturing)	1,950	390	375	2,715	- 43%

Based on the information presented above, the environmental reduction in emissions is significant. The more important topic is how geopolymer cement behaves in wellbore conditions. To measure its behaviour, one has to have a look at its properties.

Table 4.6: CO_2 Emissions of Cements (based on Davidovits J. 2013, p. 7)

CO_2 Emissions	**Calcination [CO_2/MT]**	**Crushing [CO_2/MT]**	**Silicate [CO_2/MT]**	**Total [CO_2/MT]**	**Energy Increase/Reduction**
Portland Cement (default)	1.00	0.020	-	1.020	0%
Geopolymer Cement (BFS waste material)	0.140	0.018	0.050	0.208	- 80%
Geopolymer Cement (BFS manufacturing)	0.240	0.018	0.50	0.308	- 70%

In the recent years there has been conducted experiments on chemical resistance (Khalifeh M. et al. 2016), diametrically compressive strength (Kimanzi R. et al. 2020), permeability (Khalifeh M. et al. 2017), hydraulic bond strength (Kamali M. et al. 2021), tensile strength and unconfined compressive strength (Kamali M. et al. 2021), volume changes when setting (Khalifeh M. et al. 2018), thermal conductivity (Wiktorski E. et al. 2019), and long-term durability (Khalifeh M. et al. 2016; Tian L. et al. 2021).

Table 4.7 is compound by five experimental papers done between 2016 and 2022 by Kamali M. et al. (2021), Khalifeh M. et al (2016), Khalifeh M. et al. (2018), Ogienagbon AA. et al. (2022), and Wiktorski E. et al. (2019) to examine rock-based geopolymer cement properties under wellbore conditions. Experimental values ranged from atmospheric pressure to 138, 172 and 500 bar. Temperatures ranged from room temperature to 70, 90°C and 100°C.

Table 4.7: Geopolymer Rock-based Cement Properties (based on Kamali M. et al. 2021, Khalifeh M. et al. 2016, Khalifeh M. et al. 2018, Ogienagbon AA. et al. 2022, and Wiktorski E. et al. 2019)

Property	**Units**	**Value**
[1]Permeability at t = 0	µD	0.033
[2]Permeability at t = 12 months	µD	< 0.068
[3]Modulus of elasticity	GPa (psi)	5 (725,190)
[4]Poisson ratio	-	0.19 to 0.30
[5]Cohesion	MPa (psi)	7.6 to 11.8 (1,102-1,711)
[6]Internal friction angle	°	6.3 to 11.6
[7]Tensile strength at t = 1 day	MPa (psi)	-
[7]Tensile strength at t = 5 days		~ 0.9 (± 130,530)
[7]Tensile strength at t = 7 days		~ 1.1 (± 159,540)
[7]Tensile strength at t = 28 days		~ 1.0 (± 145,040)
[8]Pumpability	Minutes	120 in atm. and 110 pressurized
[9]Thermal conductivity at 30°C, 50°C, 70°C, 100°C, 130°C, 150°C	W/(m × K)	0.74, 0.71 0.66, 0.59, 0.51, 0.48
[10]Fluid-loss	ml/30 min	356
[11]Shear bond strength in clean pipe	MPa	± 1.5
[11]Shear bond strength in rusty pipe	MPa	± 1.4
[11]Hydraulic bond strength in clean pipe	Psi	± 500
[11]Hydraulic bond strength in rusty pipe	Psi	± 500

[1-2]Measured in 100°C, 500 bar, and crude oil (Khalifeh M. et al. 2016, p. 226)

[3]Measured at 30°C and 90°C; 172 bar (Ogienagbon AA. et al. 2022, p. 7)

[4]Measured at 30°C and 90°C; 172 bar (Ogienagbon AA. et al. 2022, p. 8)

[5-6]Measured at 30°C and 90°C; 172 bar (Ogienagbon AA. et al. 2022, p. 14)

[7,8]Measured 1, 5, 7, and 28 days after curing; parameters 1.95 sg / 90°C / 170 bar (Kamali M. et al. 2021, p. 4)

[9]Measured in 1.90 sg. Samples cured in ambient pressure / 70°C for 7 days (Wiktorski E. et al. 2019 pp. 690-691)
[10]Measured in 138 bar and 70°C, value extrapolated from a 2 min experiment (Khalifeh M. et al. 2018, p. 4)
[11]Samples cured at 90°C (Kamali M. et al. 2022, pp. 6-8)

During the tensile strength test for rock-based geopolymer cement it was observed that the geopolymer had not built strength until day two, and therefore no values can be given for the tensile strength after 24 hours, i.e., t = 1 day (Kamali M. et al. 2021, p. 19).

The experimental work, shown and referred to in Table 4.7: Geopolymer Rock-based Cement Properties (based on Kamali M. et al. 2021, Khalifeh M. et al. 2016, Khalifeh M. et al. 2018, Ogienagbon AA. et al. 2022, and Wiktorski E. et al. 2019)demonstrates that rock-based geopolymer has favourable properties similar to Portland cement. Properties comparable with low chemical shrinkage, low permeability, less affected when exposed to oil-based mud compared to Portland cement, and advantageous ductility (Khalifeh M. et al. 2019, p. 353). Compared with Portland cement it posess a lower modulus of elasticity but maintains its strength with increasing temperature and pressure, while Portland cement has a declining trend when temperature and pressure increase. This is opposite for the ductility and brittleness, where the geopolymers retain a higher ductility and brittleness than Portland cement.

Khalifeh M. et al. (2016, pp. 228-229) investigated the effect of rock-based geopolymer cement over 12 months in different chemical environments; crude oil, H_2S, and brine. Geopolymer set in crude oil gave an increase in tensile strength over 12 months, while in brine it saw a decrease the first 6 months before a rapid increase of two times initial value. The specimen that got exposed to H_2S saw first an increase up to 6 months before a sharp decline reducing both compressive and tensile strength of the geopolymers, ref. Figure 4.8.

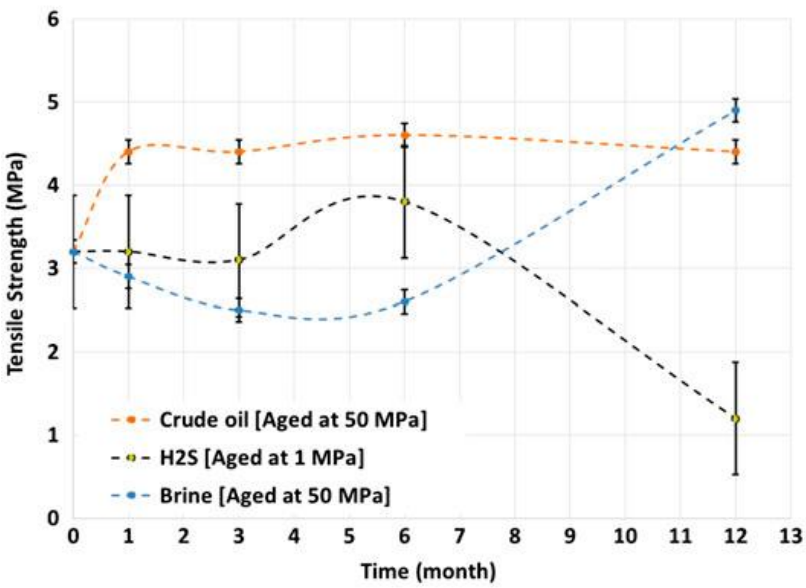


Figure 4.8: Tensile Strength of Rock-based Geopolymers (Khalifeh M. et al. 2016, figure 7)

Geopolymer-based cement demonstrated complications in an experiment with regards to pumpability/placeability in higher temperatures in the early development-phase (Khalifeh M. et al. 2014, p. 5; Khalifeh M. 2016, pp. 48-52; Khalifeh M. et al. 2018, p. 2). Pumpability/ placeability can be mitigated through adjustment in the retarder adding nanomaterials without losing its mechanical properties, demonstrated by Alvi MAA. (2020, p. 13).

When mixed together with water-based mud (WBM) types, the high water content in the geopolymer-based cement has made the specimen deteriorate resulting in lower compressive and tensile strength (Eid E. et al. 2021, pp. 3629-3632). In the case where the water content in geopolymers exceeds 5 wt.%, the contamination interrupts the geopolymerization process and leads to no hardening of the gel. Portland cements can tolerate up to 20 wt.% with water before no hardening will occur.

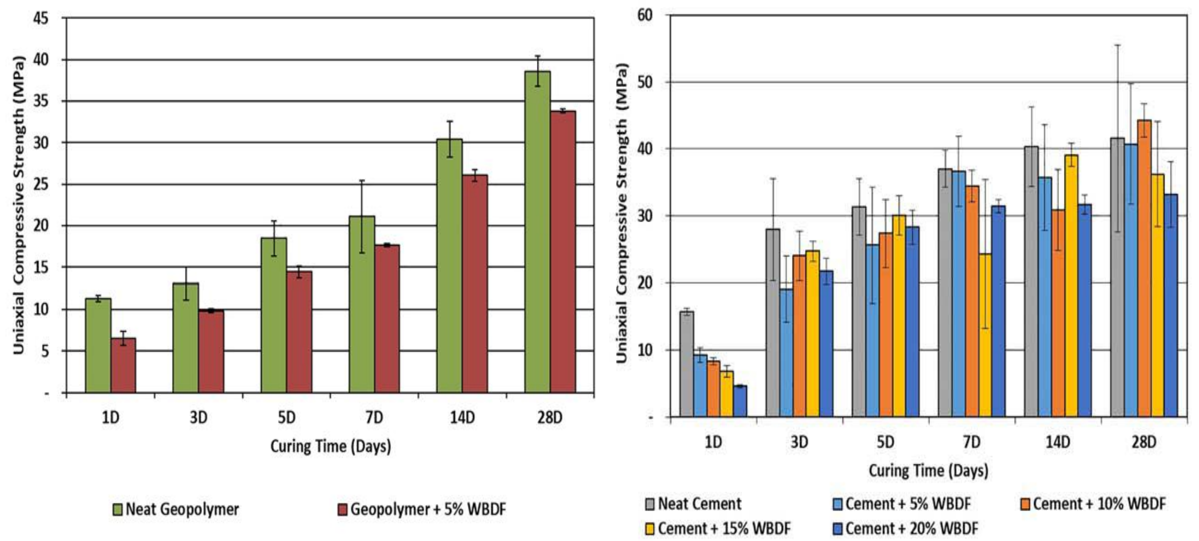


Figure 4.9: Effect of Water Contamination on Geopolymers [left] and Portland Cement [right] (based on Eid E. et al. 2021, figure 2 and 3)

Geopolymers in oil-based mud (OBM) types will at most lose its compressive strength (Eid E. et al. 2021, p. 3632). The experiments were performed with up to 20 wt.% of OBM in rock-based geopolymer cement and it would still harden and build strength. The first initial days of curing saw low compressive strengths compared to Portland cement, while after 28 days of curing the compressive strength were somehow similar up to 5 wt.% OBM. Portland cement saw for 10 wt.% and above a large decrease in the compressive strength, ref. Figure 4.10.

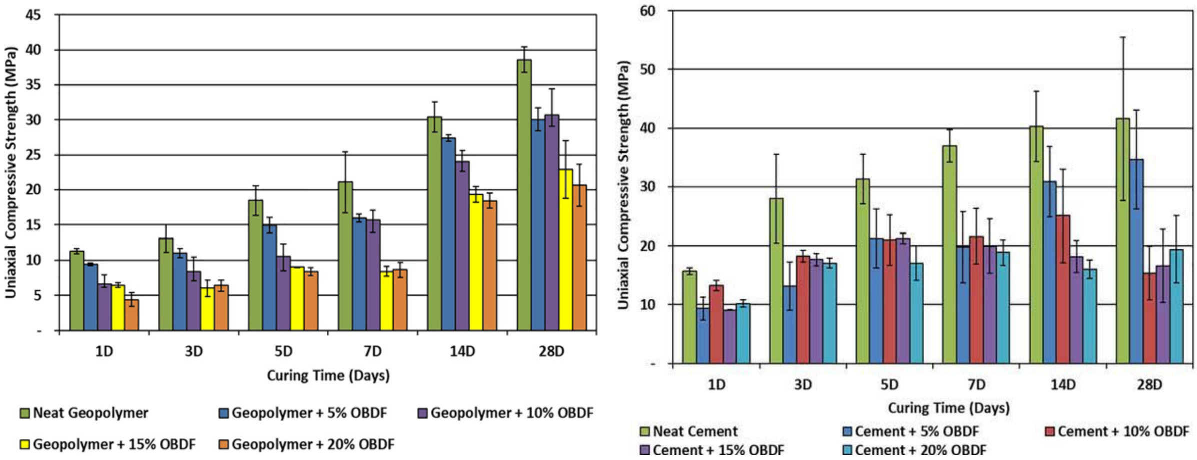


Figure 4.10: Effect of Oil Contamination on Geopolymers [left] and Portland Cement [right] (based on Eid E. et al. 2021, figure 2 and 3)

A summary of the advantages and disadvantages of rock-based geopolymer cement is given below in Table 4.8: Summary of Advantages and Disadvantages for Rock-based Geopolymer Cement

Table 4.8: Summary of Advantages and Disadvantages for Rock-based Geopolymer Cement

Rock-based Geopolymer Cement Advantages and Disadvantages	
Advantages	**Disadvantages**
• Similar properties to the cap rock	• Pumpability/placeability in elevated temperatures
• Extremely low permeability	• Degrades in corrosive environments
• Favourable compressive strength	• Loses hydrostatic column when setting
• High brittleness and ductility	• Deteriorating with high wt.% of water
• Low chemical shrinkage	• Uncertainty with respect to high temperature behaviour
• Low thermal conductivity	
• Low fluid-loss	
• High shear bond strength	
• High hydraulic bonding	

5. Qualification of Presented P&A Materials as to Presented Standards

In summary and based on the conclusion in the sub-chapters below, Table 5.1: Rock-based Geopolymer Barrier Conclusion based on Well Integrity Standards compile the end qualification results for rock-based geopolymer cement and their suitability as a barrier material based upon review and comparison of presented well integrity standards. See detailed barrier conclusion of rock-based geopolymer cement for the respective regulatory standards in Chapter 5.1, 5.2, 5.3, and 5.4, ref. Table 5.1.

Table 5.1: Rock-based Geopolymer Barrier Conclusion based on Well Integrity Standards

Conclusion whether Rock-based Geopolymer Cement Qualifies as a Barrier	
Regulatory Standards	**Approved / Disapproved**
NORSOK D-010 rev. 5	Approved ✓
OGUK well decommissioning guidelines	Approved ✓
API wellbore plugging abandonment	Approved ✓
DNV risk based abandonment of wells	Approved ✓

5.1. NORSOK D-010 Well Integrity in D&W Operations Conclusion

Referring to Chapter 2.5 NORSOK D-010 Well Integrity in D&W Operations, a permanent well barrier shall be able to seal both vertically and horizontally for a period of eternity. The barrier material shall most importantly have long term integrity properties according to Table 2.8: Requirements for Permanent Barriers (Standard Norge 2021, table 26). Below, Table 5.2 describes whether rock-based geopolymer retain required properties described in NORSOK D-010 are given below.

Table 5.2: Qualification of Rock-based Geopolymer as to NORSOK D-010

Item	Property	Requirement	Rock-based Geopolymers
a)	Long term integrity	Compressive and tensile strength, permeability and Young's Modulus should not indicate a deteriorating long-term trend.	Based on information given in Table 4.7, the long-term trend of the material does not deteriorate and instead maintain its properties, unlike Portland cement (ref. Table 4.1).
b)	Permeability	Smaller or equal to 5 µD.	Permeability measures in oil and water both shows values equal to roughly one tenth of water.
c)	Radial shrinkage	OH plugs: low shrinkage. Cased hole: long-term positive linear expansion.	Geopolymers has low chemical shrinkage and maintains its tensile strength over time compared to Portland cement which has a declining trend.

d)	Mechanical loads	Withstand foreseeable loads in the future.	Experimental tests has shown favourable modulus, strengths, and operational windows. There is however important to assess each wellbore and verify the material against maximum anticipated loads.
e)	Chemical stability	Withstand exposure to external environments without substantially affecting required integrity. Examples: H_2S, CO_2, H_2O, brines, hydrocarbons.	Geopolymer has proven to be reliable in hydrocarbons and low-content brines. It has experienced deterioration when in contact with high salinity WBM, brine and/or diluted with more than 5 wt.% of water cancelling the geopolymerization process. The chemical stability for some environments has proved to be a shortcoming for geopolymer-based cements.
f)	Bonding to tubulars	Shall bond to tubulars. If bonding cannot be achieved, the material shall for example have expanding properties as a compensating measure.	Due to naturally expanding forces in geopolymer-based cement, i.e., low shrinkage, it will bond with the tubular.
g)	Effect on tubular integrity	Not affect properties of tubulars in contact with barrier material.	In the experiments conducted by Khalifeh M. et al. and Kamali M. et al., there has been no records of deteriorating tubulars in the experimental tests performed.

Rock-based geopolymer cement has properties suitable to act as a barrier material in wells, where it has superior permeability and low shrinkage properties. Based on the papers from Eid E. et al. (2021), Khalifeh M. et al. (2014), Khalifeh M. (2016), and Khalifeh M. et al. (2018), geopolymer-based cement posess some shortcomings when it comes to high salinity brines or WBM, water content greater than 5 wt.%, H_2S-envrionments, and pumpability/placeability in higher temperatures. As pumpability/placeability were found to be a vulnerability in the early-phase, it was later demonstrated no problems with pumpability/placeability using nanoparticles as retarders.

5.2. OGUK Well Decommissioning Guidelines Conclusion

Referring to Chapter 2.6 Oil & Gas UK Well Decommissioning Guidelines, permanent barriers must have longevity. The guideline require properties that agree with long-term integrity according the Table 2.11: Requirements for Permanent Barriers (based on UKOOA 2018, pp. 12-13). A description of whether rock-based geopolymer retain the necessary properties described in OGUK Well Decommissioning Guidelines are given in Table 5.3.

Table 5.3: Qualification of Rock-based Geopolymer as to OGUK Well Decommissioning Guidelines

Item	Property	Requirement	Rock-based Geopolymers
a)	Long term integrity	Long-lasting isolation material properties, not de-bonding and cause cracks over time.	Based on information given in Table 4.7, the long-term trend of the material does not deteriorate and instead maintain its properties, unlike Portland cement (ref. Table 4.1).
b)	Permeability	Low enough permeability to prevent any flow through the barrier.	Measures has shown advantageous permeability similar to the low-end of shale, which is considered to be impermeable.
c)	Radial shrinkage	Should minimise radial shrinkage.	Rock-based geopolymers has shown that tensile and compressive strength is maintained over time due the naturally expanding forces relative to Portland cement which has a declining trend.
d)	Mechanical loads	Characteristics suitable to withstand present and future pressures and temperatures.	Experimental tests has shown favourable modulus, strengths, and operational windows. There is however important to assess each wellbore and verify the material against maximum anticipated loads.
e)	Chemical stability	It should be resistant to downhole chemicals or substances at foreseeable pressures and temperatures without substantially affecting required integrity. Examples: H_2S, CO_2, H_2O, brines, hydrocarbons, magnesium.	Geopolymer has proven to be reliable in hydrocarbons and low-content brines. It has experienced deterioration when in contact with high salinity WBM, brine and/or diluted with more than 5 wt.% of water cancelling the geopolymerization process. The chemical stability for some environments has proved to be a shortcoming for geopolymer-based cements.
f)	Bonding to tubulars	Should be designed to maximize bonding to tubulars.	Due to low shrinkage in geopolymer-based cement, it will bond with the tubular.
g)	Effect on tubular integrity	Shall not detrimentally affect properties of tubulars in contact with barrier material.	In the experiments conducted by Khalifeh M. et al. and Kamali M. et al., there has been no records of deteriorating tubulars in the experiments performed.

Rock-based geopolymer cement posess properties that is satisfactory to act as a barrier material in wells, outperforming Portland cement with regards to permeability and low shrinkage properties. A disadvantage for geopolymers is when exposed to high salinity brines or WBM, and over 5 wt.% of water dilution making the specimen deteriorate and cancelling the geopolymerization process.

5.3. API Wellbore Plugging and Abandonment Conclusion

Based on Chapter 2.7 API Wellbore Plugging and Abandonment it is possible to qualify or disqualify rock-based geopolymer cement based on well barrier and permanent abandonment requirements stated in the standard. As API states a permanently abandoned wellbore shall have a perspective of its planned service life, some or all properties given in Table 2.15. Below in Table 5.4, a summary of whether geopolymers fulfill the requirements or not are given.

Table 5.4: Qualification of Rock-based Geopolymer as to API Wellbore Plugging and Abandonment

Item	Property	Requirement	Rock-based Geopolymers
a)	Long term integrity	Long durability as a result of low permeability and porosity.	Based on information given in Table 4.7, the long-term trend of the material does not deteriorate and instead maintain its properties, unlike Portland cement (ref. Table 4.1).
b)	Permeability	As low permeability as Portland cement or the cap rock.	Measures has shown advantageous permeability similar to the low-end of shale, and 2-3 magnitudes smaller than Portland cement, as API specifically reference to.
c)	Radial shrinkage	Shall not degrade over time and lose its sealing capability.	Rock-based geopolymers has shown that tensile and compressive strength is maintained over time due the naturally expanding forces compared to Portland cement which has a declining trend and will therefore not lose its sealing capability.
d)	Mechanical loads	Shall withstand the operating environment.	Experimental tests has shown favourable modulus, strengths, and operational windows. There is however important to assess each wellbore and verify the material against maximum anticipated loads.
e)	Chemical stability	Should withstand exposure from common chemicals and micro-organisms. Common chemical exposure includes CO_2, H_2S, completion fluids, produced fluids and other wellbore fluids.	Geopolymer has proven to be reliable in hydrocarbons and low-content brines. It has experienced deterioration when in contact with high salinity WBM, brine and/or diluted with more than 5 wt.% of water cancelling the geopolymerization process. The chemical stability for some environments has proved to be a shortcoming for geopolymer-based cements.
f)	Bonding to tubulars	A barrier set in a tubular area may introduce a new flow path if the steel gets degraded over time, and considerations shall be done for this case.	Due to naturally expanding forces in geopolymer-based cement, it will bond with the tubular. Further analysis should be done assessing degradation of tubulars using geopolymers, but this is a common issue with Portland cements.
g)	Effect on tubular integrity	Not described.	No record of tubular integrity at stake has been seen in the experiments conducted by Khalifeh M. et al. and Kamali M. et al.

Rock-based geopolymer cement holds acceptable properties according to the API standard, where its expanding properties and low permeability stands out. Portland cement is considered the key barrier material and an alternative barrier material shall as a minimum equal or surpass its sealing properties. The focus on bonding to tubulars has not been covered in this thesis but it is rather assumed that bonding is greater than Portland cement based on the relative expanding properties. As stated in the papers from Eid E. et al. (2021), Khalifeh M. et al. (2014), Khalifeh M. (2016), and Khalifeh M. et al. (2018), geopolymers have faced some chemical stability problems in high brine salinities, water contents above 5 wt.%, and H_2S-environments.

5.4. DNV Risk based Abandonment of Wells Conclusion

Chapter 2.8 DNV Risk based Abandonment of Wells states that permanent barriers shall retain reliability and long-term integrity considering performance and functional requirements. A well barrier may consist of anything as long as it gives the required long-term integrity. By using risk assessments, the failure modes for different barrier materials should be compared and assessed to ultimately chose the best suitable material. Reducing the risk picture is of importance in the DNV standard.

As DNV does not have the same approach as NORSOK D-010, OGUK, and API, the qualification table is not identical in comparison. See Table 5.5 for the detailed qualification of rock-based geopolymers.

Table 5.5: Qualification of Rock-based Geopolymer as to DNV Risk based Abandonment of Wells

	Potential Failure Mode	**Potential Failure Mechanism**	**Rock-based Geopolymers**
Mainbore	Insufficient length of barrier in mainbore	- Miscalculations of density. - Slippage of barrier. - Identified top of barrier being too low.	Not relevant as this is on the operational side when setting a barrier.
	Degraded barrier function in mainbore	- Permeable barrier. - Inaccurate density of barrier. - A micro-annulus may be formed due to higher porosity in the barrier which is a result of barrier shrinkage. - Operational problems.	Geopolymers has shown advantageous permeability and several magnitudes lower than Portland cement with similar densities. Due to low shrinkage properties and paper by Ramadan MA. et al. (2021), described in Chapter 2.2, Operational problems are not covered in detail in this thesis.
Casing	Corrosion of casing	- Long or short term exposure of wellbore fluids.	Casing loads or corrosion of casing due to external factors beyond geopolymers has not been a topic in this thesis.
	Yielding of casing caused by pressure in wellbore	- Loads from formation. - Geological forces acting on well over time.	
Annulus	Insufficient length of barrier in annulus	- Slippage because of inadequate losses or density. - Not possible to do a squeeze job.	These failure mechanism address technical /operational sides and will not be covered. Cement lengths are referred to the minimum set by the other three reviewed standards.
	Degraded barrier function in annulus	- Corrosion due to H_2S. - Corrosion due to CO_2. - Previously present micro-annulus. - Previously present channels. - De-bonding and/or thermal cracking because of the Joule-Thomson effect when injecting a fluid into reservoirs that is depleted. - Poor bonding and/or channelling.	Geopolymers has proven to be reliable in hydrocarbons and low-content brines, seeing low permeabilities and high well integrity. Experiments conducted has proved challenges and degradation in H2S- and brine environments and further tests should be performed on this subject. Geopolymers experienced problems in high water contents eventually cancelling the geopolymerization process when they were exposed to more than five wt.%. The Joule-Thomson effect has not been studied.

		- Degradation due to magnesium-chloride.	Bonding and channelling is a decreasing factor using geopolymers as they has low shrinkage. Effect of degradation due to magnesium-chloride has not been studied.
	Contamination of barrier in annulus	- A micro-annulus may be formed due to higher porosity in the barrier which is a result of barrier shrinkage. - Poor removal of filter cake and cutting creates a potential hydrocarbon path where flow may migrate.	Based on presented experiments by Ogienagbon AA. et al. (2022), Kamali M. et al. (2021), Khalifeh M. et al. (2016) in Chapter 4.3, micro-annuli will less likely be created due to lower shrinkage and permeability (Ramadan MA. et al. 2021). Filter-cakes and cutting are not part this this thesis.
Formation	Formation overpressure	- Nearby injection points. - Pressure build-up with time.	Ref. Chapter 2 Literature Study, when designing the PP&A barrier material all foreseeable pressure shall be taken account for. Geopolymers have proven to be suitable for the test pressure given in Table 4.7. Experiments done on geopolymers for a long period of time shows low degradation when exposed to hydrocarbons and low-salinity brines, and when not contaminated with water.
	Exposure of fluid	- Degradation with time.	
	Geological formation as barrier	- If feasible, formation may be used as an additional barrier.	Not part of the qualification process.

Rock-based geopolymer cement with its excellent permeability and low shrinkage abilities makes it applicable as a barrier material in wells. As some part of the DNV (2020) standard addresses potential operational and technical failure modes, some of the qualification assessment is not relevant. Eid E. et al. (2021), Khalifeh M. et al. (2014), Khalifeh M. (2016), and Khalifeh M. et al. (2018) shows that exposure to corrosive environments has proved to be a weakness in geopolymer-based cement, likewise, being diluted with water resulting in a higher wt.% than five makes the specimen not set.

6. Rock-based Geopolymer Cement Advantages

Based on the technology qualification and literature review, following advantages are achieved by substituting rock-based geopolymers as a barrier material opposed to Portland cement.

6.1. Chemical Process of Geopolymer Cement

As explained in Chapter 4.3 Rock-based Geopolymer, there exist an enormous reduction in energy and CO_2-emissions by replacing standard cement types used today, characterized with the carbonisation-process, with geopolymers. As the oil & gas industry have been focusing on smarter and less cost intensive P&A-solutions the last decades, there has become a growing demand for sustainable solutions due to the climate-change discussions around the world. In Figure 6.1, a comparison of geopolymers and Portland cement with regards to average energy consumption and CO_2-emmisions are given.

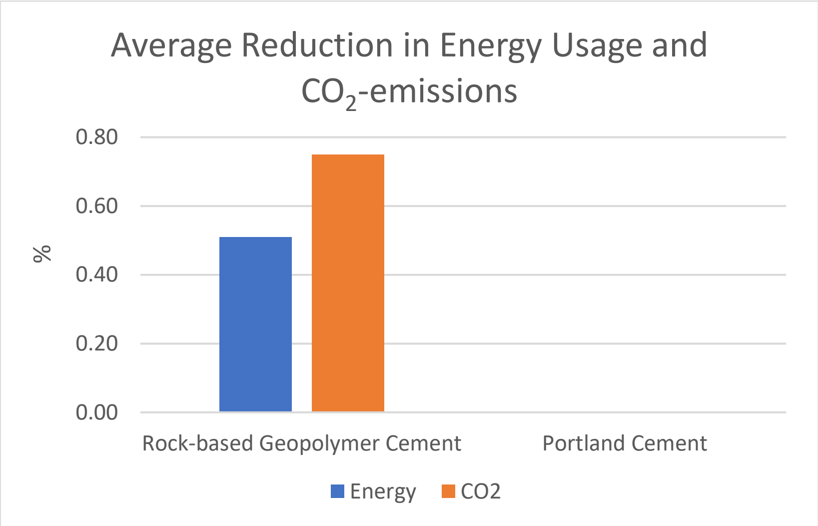


Figure 6.1: Average Reduction of Energy and CO2 with Geopolymers Relative to Portland Cement (based on Table Table 4.1 and Table 4.7)

6.2. Leakage Rate for Geopolymer Cement

Based on the presented study on leakage rate as a function of permeability by Ramadan MA. et al. (2021), it is valid particularly low permeabilities decreased the leakage rate significantly and to nearly to zero. Measured permeability of rock-based geopolymers has shown values from 0.068 µD and below, while permeability for Portland cement is ~10 µD. Comparing permeabilities for rock-based geopolymers and Portland cement, it is clear that permeability is more than two magnitudes lower for geopolymers, yielding reduced leakage rates.

A full-scale test performed by Aas B. et al. (2016), explained in Chapter 4.2, compared Portland cement with and without expanding additives to examine the variance in leakage rates and development of micro-annuli. As the cement with expanding additives posess comparable properties with regards to expansion as geopolymers, it is possible to compare them to a certain extent. See comparison of leakage rate in Figure 6.2.

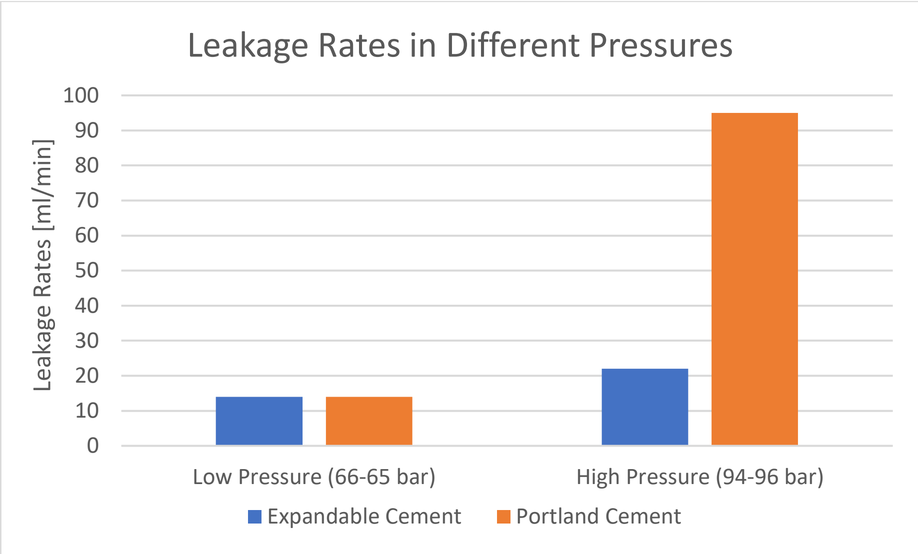


Figure 6.2: Leakage Rates Comparison Between Expandable and Portland Cement (based on Table Table 4.1 and Table 4.7)

6.3. Expandability of Geopolymer Cement

From Khalifeh M. et al. (2019) rock-based geopolymers hold low shrinkage, which can be seen in the tensile strength maturity work by Kamali M. et al. (2021). In Figure 6.3, a comparison of how tensile strength progress over a 12-month period for geopolymers and Portland is shown.

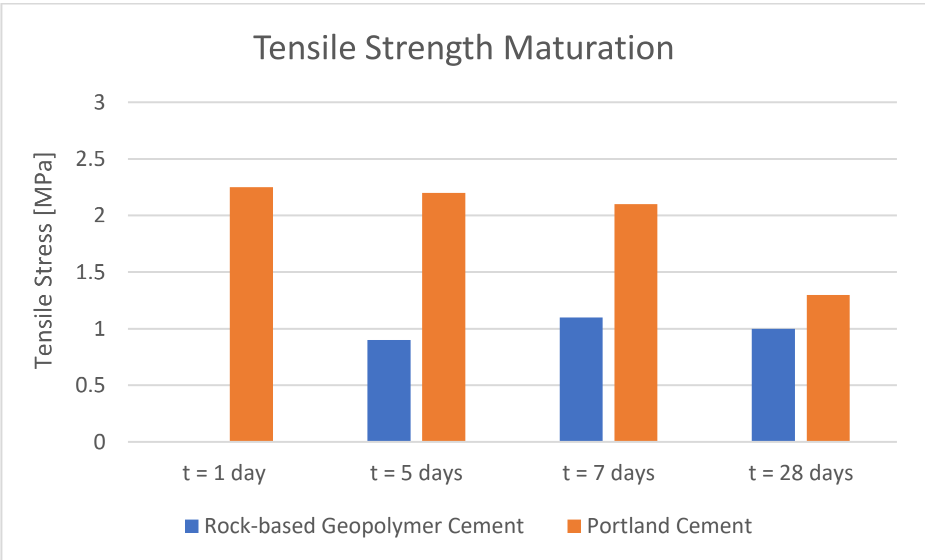


Figure 6.3: Development of Tensile Strength for Rock-based Geopolymers and Portland Cement (based on Table Table 4.1 and Table 4.7)

6.4. Hydraulic Bonding Mechanism of Geopolymer Cement

Kamali M. et al. (2022) presented performance results for rock-based geopolymers on shear bond strength and hydraulic bonding and compared them to Portland cement. The study shows that geopolymers posess significantly higher strength and bonding compared to Portland, ref. Figure 6.4 and Figure 6.5.

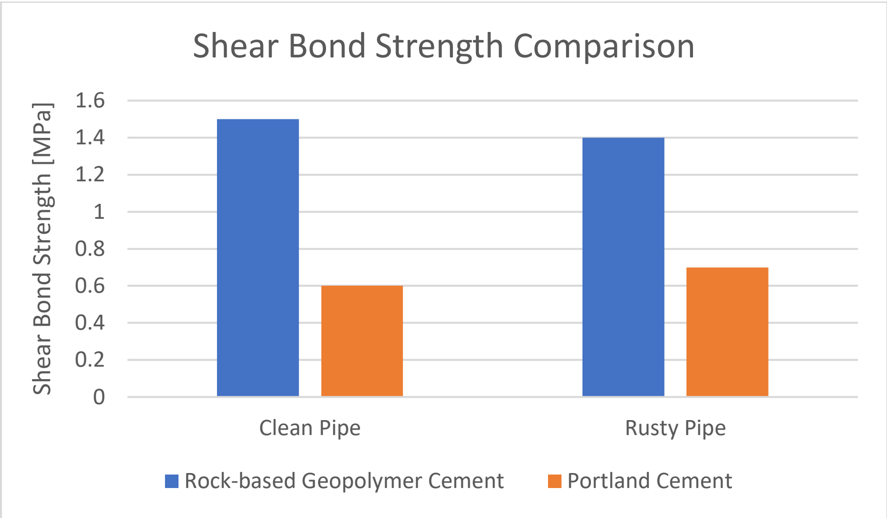


Figure 6.4: Comparison of Shear Bond Strength for Rock-based Geopolymers and Portland Cement (based on Table Table 4.1 and Table 4.7)

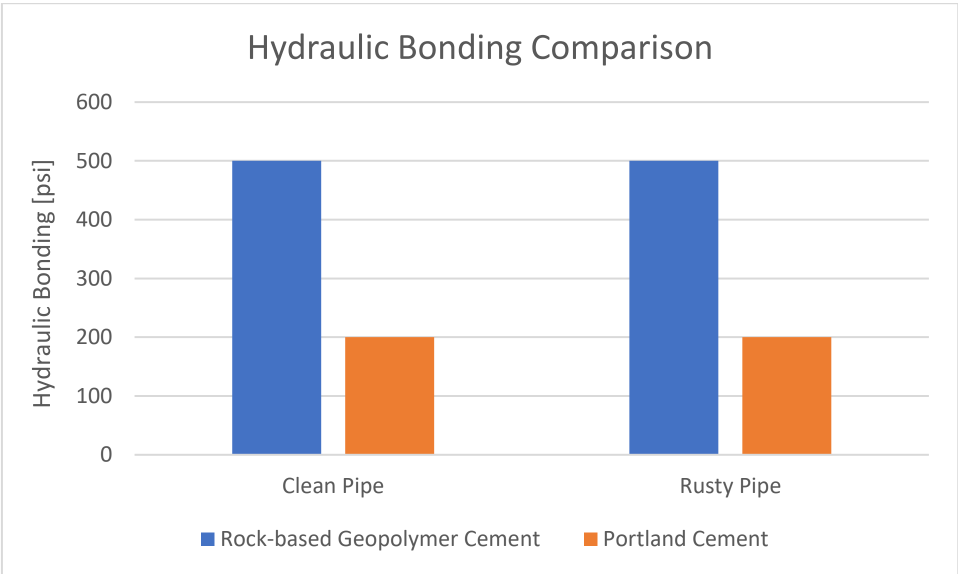


Figure 6.5: Comparison of Hydraulic Bonding for Rock-based Geopolymers and Portland Cement (based on Table Table 4.1 and Table 4.7)

PART III

Culmination

7. Defining Critical Risks with Geopolymer Cement

Before rock-based geopolymers can be used as a barrier material, it is important to be familiar with the potential failure mechanisms and modes, and related risks with geopolymers. When designing a geopolymer barrier, it is of importance to know what might go wrong and its potential failures.

7.1. Failure Modes of a Geopolymer Plug

The potential failure modes identified in Chapter 4.3 includes being exposed to high-salinity brines, diluted with water yielding water-content above 5 wt.%, and in H_2S-environments resulting in declining tensile strength over time. On the contrary, the geopolymers have proved excellent properties in OBM which should be taken advantage of.

Having high water-contents as a vulnerable point is extremely important to note as using geopolymers to seal off shallow water-bearing zones may cause an issue.

7.2. Failure Mechanisms of a Geopolymer Plug

One of the failure mechanisms of geopolymer-based cement is the longevity. It has never been exposed to wellbore environments over a period that can be compared to eternity. This problem is not only descriptive to geopolymers but also other cement types. For example the well integrity problems Portland cement has experienced over time is linked to its failure modes and shrinkage properties. Based on the presented material in this thesis and according to the risk-reducing approach DNV takes in their technology qualification recommended practice, the level of risk for rock-based geopolymer cements longevity will be significantly reduced compared to the industry

The failure mode with high water-content described in Chapter 7.1, magnify the importance of designing cement jobs for geopolymers correctly in a wellbore. By for exampling using a non-brine or non-water spacer and displacement fluid, one can mitigate dilution and the experienced problems that has resulted in cancellation of the geopolymerization process.

8. Conclusion

Rock-based geopolymer cement is in this thesis suggested as an alternative barrier material to Portland cement. It is therefore of great importance to investigate their materiality and suitability as a barrier material in permanent plug & abandonment. Based on thorough review of well barrier principles, permanent well abandonment principles, barrier material requirements, and material technology qualification the below conclusions is drawn:

Portland cement has several failure modes that sets well integrity over time at stake. The oil & gas industry has searched for commercial substitutes the last decades with few commercial alternatives reaching the market.

Based on review of the well integrity standards NORSOK D-010 (2021), OGUK (2018), API (2021), and DNV (2020) the new barrier material rock-based geopolymer cement is introduced as a substituting material.

The technology qualification standards DNV (2019) and Oil & Gas UK (2015) take an in-depth approach on how to qualify a new technology, which rock-based geopolymer is considered to be. In OGUK, geopolymer-based cement is pointed out as a potential new barrier material. Using experimental tests and quantitative results during the technology qualification process is crucial and if the new technology under review still has some uncertainties, early adoption can be done based on a thorough risk assessment.

Experimental data collected shows that geopolymers has a high ductility although seeing lower but acceptable modulus of elasticity and tensile and compressive strength compared to Portland cement. Nevertheless, the experiments have proved geopolymer-based cement even so withholds high pressures.

Chemical stability when exposed to H_2S, brines with high salinity and water dilution exceeding five percent by weight in the geopolymers has shown complications resulting in deteriorated characteristics yielding lower matrix strength. When geopolymers are intruded with over five wt.% of water, it will interrupt the geopolymerization process and lead to no hardening.

Lower permeability, expansion, fluid-loss, thermal conductivity, chemical shrinkage, and maintaining its modulus of elasticity over a span of 60°C in temperature differentials are examples of barrier advantages rock-based geopolymer cement carry opposed to Portland cement. If one supplement the significant reduction in energy usage and emission, rock-based geopolymer cement is unique and superior to Portland cement.

8.1. Proposed EAC-table for Geopolymer Cement

Due to the similarities between rock-based geopolymers and Portland cement, an EAC-table valid for geopolymer cement will be similar to the existing EAC-table for cement plugs, EAC Table 24 (Standard Norge 2021). The barrier minimum requirements and verification methods will be somehow similar. One could argue geopolymers maintain better barrier characteristics and could therefore have reduced barrier lengths but this in itself require a detailed analysis and discussion with other industry experts.

8.2. Proposal for Future Work

A list has been set together as a proposal for the future work for implementing rock-based geopolymer as a barrier material in the oil & gas industry. The list are divided into two periods, hence short- and long-term view.

Short-term: focusing on scaling up and performing further experiments to assess geopolymers failure modes and gain a good track record before advancing over to field testing. Attention should also be made on how geopolymers behave in corrosive, elevated, and water environments such as H_2S, HPHT, and water-bearing formations.

Long-term: further develop and explore geopolymers range of advantages. Eventually, scaling up to performing field tests and measure the behaviour in downhole conditions, essentially open and cased holes, and as annular barrier. This will allow analysis of how rock-based geopolymers perform as a cross-sectional barrier.

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Appendix

A1 Terms and Definitions in NORSOK D-010 (2021, pp. 1-10)

Terms (NORSOK D-010 2021, pp. 1-2)

Shall (requirement)	Expression in the content of a document conveying objectively verifiable criteria to be fulfilled and from which no deviation is permitted if compliance with the document is to be claimed. Note 1 to entry: Requirements are expressed using the verbal forms specified in ISO/IEC Directives, Part 2 clause 7.2 Table 3.
Should (recommendation)	Expression in the content of a document conveying a suggested possible choice or course of action deemed to be particularly suitable without necessarily mentioning or excluding others. Note 1 to entry: Recommendations are expressed using the verbal forms specified in ISO/IEC Directives, Part 2 Clause 7.3 Table 4. Note 2 to entry: In the negative form, a recommendation is the expression that a suggested possible choice or course of action is not preferred but it is not prohibited.
May (permission)	Expression in the content of a document conveying consent or liberty (or opportunity) to do something. Note 1 to entry: Permissions are expressed using the verbal forms specified in ISO/IEC Directives Part 2 clause 7.4 Table 5.

Definitions (NORSOK D-010 2021, pp. 2-10)

Common Well Barrier Element	Barrier element that is shared between the primary and secondary well barrier.
Formation Integrity	1) Range between fracture breakdown pressure and fracture closure pressure. 2) Fracture closure pressure. Note 1 to entry: First definition applies for legacy wells pre-dating NORSOK D-010 rev. 4 2013, and second for wells after rev. 4. Note 2 to entry: See definition of Formation Breakdown Pressure (FBP) and Fracture Closure Pressure (FCP) in Figure 6.
Fracture Closure Pressure	Pressure at which the fracture closes after the formation has been broken down. Note 1 to entry: Fracture closure pressure is equal to minimum formation stress, see Figure 6.

Inflow Test	Test where pressure on the downstream side of the test object (a well barrier or well barrier element) is reduced to create the desired differential pressure against the test object.
Leak Test	Test by applying a differential pressure on a well barrier envelope, or a well barrier element, to detect and measure a possible leak across it.
Open Hole to Surface / Environmental Plug	Last abandonment plug, set in the surface casing with function of isolating the open hole providing containment of potential contamination to the external environment. Note 1 to entry: Plug material should have permanent properties.
Permanent Abandoned	Well status where a well is permanently plugged and will not be re-entered again.
Permanent Well Barrier	Permanent well barrier that covers the full section of the well.
Low Permeability	Water permeability equal or less than 5 µD, or equal or less than thousand times the formation permeability whichever is the largest.
Plug	Device or material placed in the well with intention to prevent flow. Note 1 to entry: Can be used as a foundation or as a qualified well barrier element.
Plugging	Activities of securing a well by installing required well barriers.
Primary Well Barrier	First well barrier envelope that prevents undesired flow from a source of inflow/reservoir.
Qualification Matrix	Set of critical parameters/criteria that are determined during the process of establishing a successful track record, and that need to be fully adhered to and fulfilled in order to expect a successful outcome.
Reservoir	Formation which contains free gas, movable hydrocarbons, or over-pressured movable water.
Risk Analysis	Structured use of available information to identify hazards and to describe risk. Note 1 to entry: The risk analysis term covers several types of analyses that will all assess causes for and consequences of accidental events, with respect to risk to personnel, environment and assets. Example of the simpler analyses are SJA, FMEA, preliminary hazard analysis, HAZOP, etc. Note 2 to entry: Quantitative analysis may be the most relevant in many cases, involving a quantification of the probability and the consequences of accidental events, in a manner which allows comparison with quantitative risk acceptance criteria.
Risk Assessment	Overall process of performing a risk assessment including: Establishment of the context, performance of the risk analysis, risk evaluation, and to assure that the communication and consultations, monitoring and review activities, performed prior to, during and after

	the analysis has been executed, are suitable and appropriate with respect to achieving the goals for the assessment.
Secondary Well Barrier	Well barrier envelope that prevents undesired flow from a source of inflow/reservoir if the primary well barrier fails.
Source of Inflow	Formation with the potential for flow.
Tag(ging)	Depth verification by setting down weight from a drill string/tubing/wireline. Note 1 to entry: In this context used as load testing of a cement barrier plug as part of an indicative barrier element verification. Function of the tag is to confirm position and quality of the plug top.
Temporary Abandonment	Well status, where the well is temporarily abandoned with the purpose of re-entering the well.
Track Record	Documented record of consistent operational achievements and performance matching or exceeding expectations. Note 1 to entry: A track record is qualified by a minimum of three (3) successful operations, using the same conditions/parameters set.
Well Barrier Envelope	Set of well barrier elements encapsulating and preventing flow from a source.
Well Barrier Element (WBE)	Physical element which, in itself, does not prevent flow but in combination with other WBEs forms a well barrier envelope Note 1 to entry: See Appendix with EAC tables for acceptance criteria of each specific well barrier element. Note 2 to entry: Alternative well barrier elements/materials (to traditional mechanical elements, cement, and in-situ formation) can be used when qualified for the applicable conditions, see DNV RP-A023.
Well Barrier Element Acceptance Criteria	Technical and operational requirements and guidelines to be fulfilled in order to verify the well barrier element for its intended use.
Well Control	Collective expression for all measures that can be applied to prevent uncontrolled release of wellbore fluid to the external environment or uncontrolled underground flow.
Well Integrity	Application of technical, operational, and organizational solutions to reduce risk of uncontrolled release of formation fluids and well fluids throughout the life cycle of a well.

A2 Terms and Definitions in Oil & Gas UK

OGUK Well Decommissioning Guideline (2018, p. 6)

Combination Barrier	Where primary and secondary permanent barriers are combined into a single large permanent barrier.
Good Cement	Cement that has been verified as to quantity and quality as stated in Section 4 of these guidelines
Impermeable	A formation or material is considered impermeable when it has sufficiently low permeability so as to prevent flow, i.e., it is impermeable to flow.
Maximum Anticipated Pressure	Maximum pressure expected in the wellbore of formation in the future following permanent well decommissioning. This may include the possible effects of future developments or the recharge of the reservoir.
Permanent Well Decommissioning	The permanent isolation from surface and from lower pressured zones, of penetrated zones with flow potential in any well that will not be re-entered.
Permanent Barrier	A verified barrier that will maintain a permanent seal. A permanent barrier must extend laterally across the full cross section of the well and include all annuli. When considering isolation from surface, the first barrier above the point of influx is referred to as the **primary barrier**; the next barrier above the point of influx is referred to as the **secondary barrier**.
Zone with Flow Potential	Sequence of rock that is capable of flow of fluids. See section 2.

OGUK Guidelines on Qualification of Materials for the Abandonment of Wells (2015, pp. 6-11)

Abandonment	The activities conducted once an oil well has ceased to be economically viable. Abandonment will normally involve placing barrier plugs to isolate formations from each other and from the surface. It will also involve removal of production facilities and remediation of the well site. This is referred to as “permanent abandonment” if there is no intention to ever re-enter the abandoned part of the wellbore. Where such an intention exists, temporary abandonment will be conducted.

Barrier Material	Material used in a well to provide a seal as part of a permanent barrier.
Barrier Plug	A volume of barrier material used as either a temporary barrier or permanent barrier.
Bridge Plug	Traditionally, a device that can be set in a well to isolate the lower part of the wellbore. Bridge plugs may be classified as either permanent or retrievable and can also be provided as an inflatable device. In the context of well abandonment, a bridge plug can be used a mechanical device to provide a solid base for setting a permanent barrier such as a cement plug.
Geopolymer	Polymeric aluminosilicate material.
Good Cement	Cement that has been verified as to position, quantity and quality, as per Guidelines for the Abandonment of Wells (Issue 5) Oil & Gas UK (now Well Decommissioning Guidelines, issue 6).
Mechanical Plug	A device used to produce a seal in a casing through the application of forces by mechanical means.
Permanent Barrier	A verified barrier that will maintain a permanent seal. A permanent barrier must extend across the full cross section of the well and include all annuli.
Permanent Barrier Material	Material used in a well to provide a seal as part of a permanent barrier.
Temporary Barrier	A verified barrier that is designed to maintain a seal over a finite period of time for the purpose of suspension of operation. A temporary barrier is not required to extend across the full section of the well and include all annuli.
Viscous Pill	In the context of well abandonment a pill can be used to provide a nominally quasisolid base for setting a permanent barrier such as a cement plug. Pills can take the form of viscous pills, whose viscosity acts to limit mobility, *viscous reactive pills* whose viscosity derives from a chemical reaction when in contact with cement or other substances. A pill will typically be “weighted” – of suitable density to allow it to locate itself at the correct depth.

A3 Terms and Definitions in API RP 65-3 Wellbore Plugging and Abandonment

Barrier	A component or practice that, if properly installed, contributes to the total system reliability by preventing liquid or gas flow.
Cement	Any material or combination of materials fluidized and pumped into the well to provide a seal. **Note:** This includes pumpable sealants containing Portland cement, pozzolan blends, blast furnace slag bends, phosphate cement, hardening ceramics, resins, geo-polymers or other appropriate materials.
Plug	A verifiable barrier located within the wellbore that may be mechanical or cement.

A4 Terms and Definitions in DNV Recommended Practices

DNV-RP-E103 Risk based Abandonment of Wells

Failure mode	“Potential or observed manner of failure on a specified level of a well barrier or well barrier element.”
Impermeable	Impermeable to flow.
Level of risk	“Magnitude of a risk or combination of risks, expressed in terms of the combination of consequences and their likelihood.”
Permanent well barrier	“Combination of one or several well barrier elements (WBE’s) that contain fluids within a well to seal a source of inflow.”
Plug and abandonment	“Action taken to ensure permanent isolation of fluids and pressures from exposed permeable zones along well trajectory by installation of well barriers.”
Well barrier element	“A physical element which by itself does not prevent flow but in combination with other WBE’s forms a well barrier.”
Well integrity	“The ability of a well to perform its required function effectively and efficiently while preventing uncontrolled release of formation fluids along the wellbore throughout the life of the well.”

A5 OGUK Detailed Experimental Work Plan for Type A Materials – Guidelines on Qualification of Materials for the Abandonment of Wells

Table A0.1: Detailed Experimental Work Plan (OGUK Guidelines on Qualification of Materials for the Abandonment of Wells 2015, table 4)

Property	Require-ment	Test	Ageing required?	Acceptance criteria Before ageing	 After ageing
PERMEATION TESTING					
Nitrogen permeability	1	See Section 8.2.1	Yes	See Section 7. Calculated release rate (Appendix 6) < 0.03 m^3/year but no more than 10 µDarcy.	< 50% increase
Diffusion coefficient	3	-	-	-	-
INTERACTION WITH FLUID					
Dry mass	1	Measurement of mass after drying to constant mass at 105°C (221°F)	Yes	-	** < 3% loss in dry mass relative to that before aging
Absorption	3	-	-	-	-
DIMENSIONAL STABILITY					
Expansion / Swelling					
During hardening	1	API RP 10B-5 ring test	No	< 1.0% linear shrinkage	-
Hardened	1	API RP 10B-5 ring test	Yes	-	** < 1.0% linear shrinkage
Shrinkage					
During hardening	1	API RP 10B-5 ring test	No	< 1.0% linear shrinkage	-
Hardened	1	API RP 10B-5 ring test	Yes	-	**0% linear shrinkage
Differential thermal expansion	1	ASTM E228	No	Coefficient of thermal expansion ± 5 K^{-1} x 10^{-6} of casing	-
Creep	1	ASTM C512-10	No	< 1.0% linear strain	-
MECHANICAL TETING					
Triaxial Testing	3	-	-	-	-
Cohesion	3	-	-	-	-
Poisson's ratio	3	-	-	-	-
Internal friction angle	3	-	-	-	-
Hydrostatic compressive yield	3	-	-	-	-
UCS	1	API RP 10B-2	Yes	> 1.4 MPa (200 psi)	> 1.4 MPa (200 psi)

Tensile strength	1	ASTM C496	Yes	> 1.0 MPa (145 psi)	> 1.0 MPa (145 psi)
Elastic modulus	2	ASTM C469	Yes	-	-
Hardness	2	ASTM E384	Yes	-	-
OTHER CHARACTERISTICS					
Bond Strength					
Shear bond strength	1	See Section 8.6	Yes	* > 1 MPa (145 psi)	* > 1 MPa (145 psi)
Tensile bond strength	3	-	-	-	-
Decomposition temperature	3	-	-	-	-
Density	2	ASTM C138	Yes	-	-
Stress relaxation	3	-	-	-	-

* Minimum shear bond strength limit has been arrived at based on a calculation detailed in Appendix 11.

** Priority after-ageing test.

A6 EAC Table 55 Alternative Barrier Material – NORSOK D-010 (2021, pp. 249-250)

Features	Acceptance criteria	See
A. Description	The well barrier element (WBE) consists of a barrier material in solid or semi solid state or a suspension thereof that forms a barrier in the wellbore, inside production string or casing/liner, or behind casing/liner. Note 1: This EAC table only applies to barrier materials other than cement. Note 2: This table covers the requirements to qualify an alternative/new barrier material.	NORSOK D-001
B. Function	The purpose of the plug material is to prevent flow of formation fluids inside a wellbore, between formation zones and/or to the environment outside the well construction to surface/seabed environment.	
C. Design (capacity, rating, and function), construction and selection	1) A new barrier material shall undergo a qualification process as specified in (or similar to) UK Oil and gas Guideline on qualification of materials for the abandonment of wells [62] and/or DNV RP-A203 “Qualification of New Technology” [59] That Qualification process shall be documented. 2) Prior to installation, the properties of the barrier material shall have been verified by laboratory testing to ensure functional, sealing, and mechanical capabilities. This shall be documented in Product certificate issued by the manufacturing plant/lab and subsequently approved by the end user. 3) Barrier material used to isolate sources of inflow containing hydrocarbons shall be designed to prevent gas migration and be suitable for the well environment (e.g., temperature, CO_2, H_2S). 4) The barrier material shall be designed for the highest differential pressure and highest downhole temperature expected including installation and test loads and shall be able to withstand pressure from below without upward movement. 5) If used for permanent abandonment applications, the alternative barrier material shall fulfil the requirements stated in Clause 10, and in particular Table 26, as well as paragraphs 10.3.1, 10.3.2, and 10.6.2. 6) The following shall be considered for any new barrier material to be used: a) Foundation and anchoring for the plug material; b) sensitivity to loss of hydrostatic pressure; c) sensitivity to contamination from wellbore and/or formation fluids; d) ability to remove the material in the event that a well shall be re-entered; e) the risk of fluidization or disintegration of the barrier material shall be assessed; f) if an alternative material is used in a well for the first time, its installation shall be verified in the same	UK Oil and Gas, Guidelines on qualification off materials for the abandonment of wells [62] DNV RP-A203 [59]

	manner as for the tests that were performed as part of the qualification process. The minimum barrier length shall be determined based on a sealing capability that is documented to be equal to or greater than what is provided by the required cement length in EAC Table 22 and EAC Table 24. The minimum WBE material length shall be documented to fulfil requirements set in 10.6.3.	
D. Initial test and verification	1) Internal WBE shall be verified using at least one of the methods below: a) Pressure test, either in the direction of flow or from above. If the WBE is set on a pressure tested foundation, a pressure test is not required. It shall be verified by tagging; b) tag/load test with drill pipe or wireline; c) any other alternative verification method that is documented and proven to be suitable for the particular type of alternative barrier material being used. 2) External WBE shall be verified using at least one of the methods below: a) Bonding logs. Logging methods/tools shall be selected based on ability to provide data for verification of bonding. The measurements shall provide azimuthal/segmented data. The logs shall be verified by qualified personnel and documented; b) application of a pressure differential across the interval; c) downhole acoustic leak-off test; d) any other alternative verification method that is documented and proven to be suitable for the particular type of alternative barrier material being used. 3) The installation of the alternative material WBE shall be verified through evaluation of job execution.	
E. Use	None	
F. Monitoring (regular surveillance, testing and verification)	Monitoring required in the following scenarios: a) First use of a new alternative barrier material. b) Temporary Abandonment (wells with monitoring) and suspension.	
G. Common WBE	To be evaluated on a case by case basis after performing an engineering review and a risk assessment.	

A7 Detailed Barrier Comparison of NORSOK D-010 rev. 4 and rev. 5

Table A0.2: Detailed Barrier Comparison of NORSOK D-010 rev. 4 and rev. 5

NORSOK D-010 rev. 4 (2013)		**NORSOK D-010 rev. 5 (2021)**		**Assessment Details**
Topic	**Description**	**Topic**	**Description**	**Comments**
4 General principles 4.7.3 Maintenance program and procedures	-	4 General principles 4.7.3 Maintenance program and procedures	… "A WBE's reliability should be measured by systematically recording any failure during operation or testing."	Additional text added in new revision.
9 Abandonment activities 9.6.2 Well barrier acceptance criteria	… "Control lines and cables shall not form part of the permanent well barriers.	10 Abandonment activities 10.6.2 Well barrier acceptance criteria	… "In general, continuous cables and control lines shall not form part of the permanent well barriers. However, cables and control lines can form part of a permanent well barrier if isolation in these control lines is achieved. Assessment of potential leak paths and the plugging thereof, as well as degradation of the cable or control line material itself, shall be conducted."	Rev. 5 removed requirement that equipment except tubulars cannot be part of a barrier. If a thorough risk assessment of potential leak paths and failure modes yields an acceptable barrier, cables and control lines may form part of the barrier. For normal cement types that has known failure modes such as shrinkage, it would not be acceptable to have control lines forming part of the barrier.
9 Abandonment activities 9.6.2 Well barrier acceptance criteria	Not included	10 Abandonment activities 10.6.2 Well barrier acceptance criteria	Table 26 "Well barrier material requirements", page 99.	Additional well barrier acceptance criteria-table added in the new revision.
9 Abandonment activities 9.6.3.1 External WBE	"The requirement for an external WBE is 50 m with formation integrity at the base of the interval. If the casing cement is verified by logging, a minimum of 30 m interval with acceptable bonding is required to act as a permanent external WBE. Logging of casing cement shall be performed for critical cement jobs and for permanent abandonment where the casing cement is a part of the primary	10 Abandonment activities 10.6.3.1 External WBE	"The external WBE shall be adjacent to a sealing formation with formation integrity exceeding the maximum expected pressure at the base of each interval. When the same annulus cement is a part of both the primary and secondary well barriers, the annular cement shall be verified by logging, or if applicable, by identifying two separate intervals and pressure testing each barrier interval in order to verify each barrier element independently.	Rev. 5 eased the requirement of the annulus cement. Instead of having one interval of 30 m good cement, it may now be two intervals, each 15 m. Small adjustment; changed naming from "casing cement" to "annulus cement".

	and secondary well barriers.”		Pressure integrity shall be verified by application of a pressure differential across each interval, which should be no more than 30 m MD long. Monitoring shall facilitate detection of small leaks.”	
-	-	10 Abandonment activities 10.6.3.4 Assessment of reduced length of WBE	“… a WBE that has a length shorter than what is specified in EAC Table 22 and EAC Table 24, a thorough risk assessment shall be done on possible leakage paths outside the well barrier element.”	New sub-chapter, where rev. 5 introduced that a shorter length of the WBE might be acceptable pending on a thorough risk assessment.
-	-	10 Abandonment activities 10.6.3.5 Reduced length of a combined external and internal WBE	… “The uncertainties related to geological setting and cement/plug material quality shall be addressed in a risk assessment, and shall as a minimum include a sensitivity on: a. Predicted final res. pressure; b. Cement/plug material quality and integrity; c. Bonding and interface strength; d. Formation fractures; e. Temperature effects; f. Micro-annulus.	
-	-	10 Abandonment activities 10.6.3.6 Reduced length of an internal WBE	“General length requirement for an external barrier is met, but the internal WBE does not meet the length requirements… A risk assessment shall be performed, which, as a minimum, shall consider the following: a. Predicted final res. pressure; b. Cement/plug material quality and integrity; c. Bonding and interface strength between casing and cement/plug material; d. Temperature effects; e. Micro annulus;	

			f. Potential leak paths due to the reduced internal WBE.”	
WBE Acceptance Table 22 – Casing cement	… ”Planned casing cement length: a. … b. General: Shall be minimum 100 m MD above a casing shoe/window.	WBE Acceptance Table 22 – Annulus cement	… ”Planned annulus cement length: a. … b. General: Should be minimum 100 m MD above a casing shoe/window for kick tolerance purpose and minimum 200 m MD if next section will penetrate a source of inflow.	A requirement was added in rev. 5 regarding having minimum 200 m MD annulus cement if the next section is supposed to drill through a source if inflow.
WBE Acceptance Table 24 – Cement plug	“The minimum cement plug length shall be (cased hole cement plugs): 50 m MD if set on a mechanical/cement plug as a foundation, otherwise 100 m MD.	WBE Acceptance Table 24 – Cement plug	“The minimum cement plug length shall be (cased hole cement plugs): 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 can be 30 m.	Rev 5. decreased the required cased hole cement plug length when set on a fundament in the case where the annular barrier has been qualified with 30 m MD.
WBE Acceptance Table 24 – Cement plug	-	WBE Acceptance Table 24 – Cement plug	“Verification (cased hole): Tagging… Tagging may be omitted if all the following conditions are met: a. The cased hole cement plug has previously been verified by tagging for the same casing/ borehole geometry, cement and fluid system; b. A successful and auditable track record has been established, using a qualification matrix with a documented parameter; c. 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 cement plug	Rev. 5 added that tagging of a cement plug can be omitted if there exist a track record of other wells with similar wellbore parameters.

			operation according to the parameter set defined in the qualification matrix, the cement plug shall be verified by tagging and pressure testing. d. The verification of the design and execution of the cement plug and the fulfilment of the qualification matrix criteria shall be documented and approved."	
WBE Acceptance Table 24 – Cement plug	"If one continuous cement plug (same cement operation) is defined as part of the primary and secondary well barriers; it shall be verified by drilling out the plug until hard cement is confirmed: 1. An open hole cement plug extended into the casing shall be pressure tested. …"	WBE Acceptance Table 24 – Cement plug	"If one continuous cement plug (same cement operation) is defined as part of the primary and secondary well barriers; it shall be verified by drilling out the plug until hard cement is confirmed: 1. An open hole cement plug extended into the casing shall be pressure tested. a. If the continuous cement plug is set in favourable conditions for cementing operations, such as in seawater/brine and on top of a reliable, verified foundation, it may be verified by tagging/load testing only. …"	Rev. 5 added a possibility of omitting the pressure test for a continuous set cement plug extending from open hole to cased hole if the operational conditions have been favourable. It is adequate to tag and load test the plug.

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