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A Study of How to Implement Alternative Well Plugging Materials in Governing Regulations

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HOVEDOPPGAVE/DIPLOMA THESIS/MASTER OF SCIENCE THESIS

Kandidatens navn/The candidate's name:	Fredrik Skjeldestad
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Utfyllende tekst/Extended text:

Background:
Plug and abandonment of wells faces a rapidly growing demand. Therefore the industry has increased its focus on this time-consuming and costly operation.
Alternative plugging materials, such as ThermaSet and Sandaband, has been introduced to save time, ensure better performance and avoid costly repair operations of cement plugs.
Well abandonment is regulated by NORSOK D-010, where Rev. 3 from 2004 is the current version. However, the requirements are mainly based on a standard cement system as plugging material.

Task:
1) Describe the requirements to temporary and permanent well abandonment, as given in Rev. 3 of NORSOK D-010.
2) Discuss how and when alternative plugging materials may save time and/or enhance plug performance.
3) Make a proposal for how the governing regulations should be adjusted to take in to account the alternative plugging materials.
4) Evaluate if the adjustments would, in any way, have lowered the requirements to P&A plugs.

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Sigbjørn Sangesland

Samandrag

Styrande lover og forskrifter for petroleumsaktivitet på norsk sokkel viser til bransjestandarden NORSOK D-010 for tekniske og funksjonelle krav til Plug & Abandonment (P&A) operasjonar. Den siste revisjonen av dette dokumentet vart gjort i 2004, og sidan då har det skjedd mykje i utviklinga av P&A teknologi.

Denne rapporten vil først skildre dagens NORSOK D-010 krav for P&A operasjoner. Basert på desse krava, vil det følgje ei evaluering av sement og tilsetjingsstoff, og også ei evaluering av dei nyutvikla alternative materiala ThermaSet og Sandaband som potensielle pluggematerial. Desse materiala viser seg å være potensielt gode alternativ, og kan med fordel erstatte sement i visse situasjonar og under visse forhold, for å spare tid, pengar, og sikre betre ytelse som isoleringsmateriale.

Sidan den siste revisjonen av NORSOK D-010 i hovudsak er basert på sement som pluggemateriale, bør den verte meir generalisert, og optimalisert for å leggje til rette for bruk av dei nye materiala. Etter ei evaluering av pluggemateriala basert på dagens gjeldande krav, vil denne rapporten komme med forslag til justeringar og endringar i NORSOK D-010 for å tilpasse standarden til dei nye alternative materiala. Dei føreslåtte endringane omfattar generalisering av krava for sement, oppdateringar og inkludering av meir informasjon i brønnbarriereskisser, og utvikling av nye konkrete krav for dei to nye alternative materiala ThermaSet og Sandaband.

Til slutt vil dei føreslåtte endringane evaluerast for å vurdere om justeringane vil auke eller redusere nivået av tryggleik i NORSOK D-010-standarden. Mesteparten av dei føreslåtte justeringane er forventa å auke nivået av tryggleik, og ingen av endringane er forventa å senke nivået av tryggleik i standarden.

Ein ny revisjon av NORSOK D-010 (Rev. 4) er allereie annonsert, og er venta å vere ferdig i slutten av 2012. Andre område som òg burde vurderast å jobbe med i framtida er å utvikle og implementere eigne norske standardar for testing og kvalifisering av alternative pluggematerial, i tillegg til å utvikle og betre nye og gamle material vidare.

Summary

The governing requirements and regulations for petroleum activities on the Norwegian Continental Shelf (NCS) refers to the industry standard NORSOK D-010 for technical and functional requirements for Plug & Abandonment (P&A) operations. The last revision of this document was done in 2004, and since then, a lot has happened in the area of P&A technology development.

This report will first describe the current NORSOK D-010 barrier requirements for P&A operations. Based on these requirements, an evaluation of cement materials and additives will follow, and also an evaluation of the newly developed alternatives ThermaSet and Sandaband as potential plugging materials. These materials all turns out to be potentially good alternatives, and could beneficially replace cement in certain environments and conditions to save time, money, and ensure better performance as a sealing material.

However, at the time of the last revision, the NORSOK D-010 standard was mainly based on cement as the standard plugging material, and should therefore be more generalized and optimized for the implementation of the new materials. After evaluating the plugging materials, this report will make proposals for adjustments in the NORSOK D-010 to better implement the new alternative materials. The proposed changes include generalization of the requirements for cement, updates and inclusion of more information in well barrier schematics, and development of new specific requirements for the two new alternative materials.

In the end, the proposed changes will be evaluated to assess if the adjustments would increase or reduce the level of safety in the NORSOK D-010 standard. Most of the proposed adjustments are expected to increase the level of safety, and none of the changes are expected to lower the level of safety in the standard.

The next revision of NORSOK D-010 has already been announced, and is expected to finish late 2012. Other areas that should be assessed in the future are to develop and implement new standards for testing & qualification of alternative materials for use as barrier elements in P&A operations on the NCS, in addition to further development and improvement of new materials.

Preface

This project was written at the department of Petroleum Engineering and Applied Geophysics, in the spring of 2012, at the Norwegian University of Science and Technology (NTNU).

First, I would like to thank my academic supervisor for this project, Professor Sigbjørn Sangesland from NTNU, for helping me set up this thesis, and for guidance and useful comments during my work with this thesis. I would also like to thank my external supervisor from SINTEF, Torbjørn Vrålstad for excellent guidance and feedback, and for sharing your knowledge with me.

In addition, I would like to thank Vidar Rygg from Sandaband Well Plugging AS, and Colin Beharie and Ingvar Sveinsvoll from Wellcem AS, for providing information and answering my questions about the new alternative plugging materials.

Finally, I would also like to thank Tore Fjågesund from Wellbarrier AS, for providing me with some of the illustrations used in this thesis.

Trondheim, 2012

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Fredrik Skjeldestad

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List of Abbreviations

API	American Petroleum Institute
HPHT	High Pressure / High Temperature
HSE	Health, Safety and Environment
ISO	International Standards Organisation
MD	Measured Depth
NCS	Norwegian Continental Shelf
NORSOK	Norsk Sokkels Konkuranseposisjon
OLF	The Norwegian Oil Industry Association
PSA	Petroleum Safety Authority Norway
P&A	Plug & Abandonment
PC	Portland Cement
TVD	True Vertical Depth
WBE	Well Barrier Element
WBEAC	Well Barrier Element Acceptance Criteria
WBEACT	Well Barrier Element Acceptance Criteria Table
WBS	Well Barrier Schematics
WIF	Well-Integrity Forum

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1 Introduction

After a well has finished its life, or for some other reason needs to be closed down temporary or permanently, the well needs to be plugged & abandoned. P&A operations can contribute with up to 25% of the total drilling costs of exploration wells offshore Norway [25]. Cost efficient P&A technology is therefore necessary. With an increasing number of old wells that need to be permanently plugged & abandoned, the industry is now focusing more on these time consuming and costly operations.

The governing requirements and regulations for petroleum activities on the Norwegian Continental Shelf (NCS) point to the industry standard NORSOK D-010 for technical and functional requirements for P&A operations [15]. Since the standard was last revised in 2004, a lot has happened in the industry regarding development of new P&A technology. Traditionally, P&A is performed with cement, but more and more failing cement jobs, leading to time consuming and costly operations, has led the industry into considering and developing alternative plugging materials. Replacing cement as a plugging material can save time, money, and even more important, it can ensure better performance, and prevent costly repair operations. Development and qualification of new alternative materials like Sandaband and ThermaSet can therefore be regarded as some of the most important technological achievements in P&A the last decade.

However, the industry standard NORSOK D-010, at the time of the last revision, was mainly based on cement as the standard plugging material, and is therefore not optimised for the implementation of the new materials. It is important to prepare and optimise the standards for the new materials to keep up with the technological development. The standards should be improved by adjustment of the current requirements, and development of new specific requirements for the new materials. This would encourage the use of alternative materials, but at the same time ensure a high level of safety. The object of this thesis is to evaluate the current requirements, and propose changes and adjustments to improve the standards, to implement new alternative materials for use in P&A operations.

2 P&A in General

P&A is the well action where you secure the well with one or more plugs, and abandon the well temporarily or permanently. Temporary abandonment is defined as the well status where the well is abandoned and/or the well control equipment is removed, with the intention that the operation will be resumed within a specified time frame (from days up to several years). Permanent abandonment is defined as the well status where the well or part of the well, will be plugged and abandoned permanently, and with the intention of never being used or re-entered again [25].

The main purpose of a permanent P&A is to isolate the subsurface formations that are penetrated by the well [1]. While it is important to seal the reservoir, an ideal P&A should also seal all other permeable fluid-bearing formations. In addition to preventing fluid from migrating to the surface, the P&A should also prevent the fluid from cross-flowing from one subsurface formation to another. The most important reason to prevent oil or gas from leaking to the surface is that it may pose a threat to the environment. Cross-flow to a groundwater source formation may pollute the water used as drinking water in some countries. If this is the case, gas can be especially dangerous if it enters the water pipe system, because this may in worst case enter households and come out of taps when these are turned on [3].

On the NCS, and other areas where drinking water is not a concern, cross-flow should still be avoided, because of pressure communication. Although one well in a field is being abandoned, there may be other wells in the same reservoir section that are still producing, so communication along an abandoned well is not desirable, because this can direct pressure away from the reservoir.

Experts estimate that a high proportion of seals placed in wells may be faulty [1]. Leaking seals pose risks to the environment and must be repaired, but remedial plugging operations are difficult and expensive. Sealing a well properly at the outset is far easier, even if the initial financial outlay appears high.

3 Acts and Regulations

The Petroleum Act of November 29th 1996 No 72 [10], under the jurisdiction of the ministry of Petroleum and Energy, governs the resource management and petroleum activities on the NCS. The Petroleum Act is the foundation for supplementary governing regulations stipulated by different regulatory authorities regarding other aspects of petroleum activities.

The Petroleum Safety Authority Norway (PSA), under the jurisdiction of the ministry of Labour, is responsible for developing and enforcing regulations that govern Health, Safety and Environment (HSE) on the NCS. The PSA have stipulated several regulations in accordance with the Petroleum Act §10–18, and the most central regulations for petroleum activities offshore are:

- The Framework HSE regulations
- The Management regulations
- The Facilities regulations
- The Activities regulations

These regulations are risk based, and the purpose is to reduce, to the greatest extent possible, the risk of accidents, injuries, and damage to the environment. The regulations are mostly formulated as functional requirements. This means that the requirements expresses what result the product, process or service is to produce. It gives the operators freedom to choose how to fulfil the requirements, but it also gives full responsibility to the operator regarding risk analysis and qualification of the solutions. The functional requirements also make the regulations adaptive for technological improvements in the industry. The functional requirements remain the same, even though the technological solutions for fulfilling them improve.

The PSA have also issued guidelines supplementary to the regulations. Regulations and guidelines should be viewed in context to obtain the best possible understanding of the level set by the regulations. The purpose of a guideline is to demonstrate how provisions in the regulations can be met and to give information of the legislation. Regarding HSE, guidelines to the individual requirements of the regulations recommend solutions as a way of fulfilling these requirements, usually in the form of recognised norms, such as industry standards. If a guideline-recommended solution is chosen, the functional requirement can generally be considered fulfilled. If an alternative solution is chosen, the responsible party must carry out an internal nonconformity assessment that clarifies whether the chosen solution fulfils the regulatory functional requirement just as good as, or better than the recommended one. If the responsible party intends to use a solution that differs from a specific requirement in the regulations, or wishes to use a solution that entails a lower level for HSE than the regulatory functional requirement, the responsible party must apply for the authorities' exemption [15].

The most important sections of the petroleum regulations regarding P&A operations are §48 – Well Barriers in the facilities regulations, §85 – Well Barriers in the activities regulations, and §88 – Securing Wells in the activities regulations:

§48 – Well Barriers in the facilities regulations states [14]
"When a well is temporarily or permanently abandoned, the barriers shall be designed such that they take into account well integrity for the longest period of time the well is expected to be abandoned. The well barriers shall be designed such that their performance can be verified."

§85 – Well Barriers in the activities regulations states [13]
"During drilling and well activities, there shall be tested well barriers with sufficient independence. If a barrier fails, activities shall not be carried out in the well other than those intended to restore the barrier."

§88 – Securing Wells in the activities regulations states [13]
"All wells shall be secured before they are abandoned so that well integrity is safeguarded during the time they are abandoned. For subsea-completed wells, well integrity shall be monitored if the plan is to abandon the wells for more than twelve months. It shall be possible to check well integrity in the event of reconnection on temporarily abandoned wells. Abandonment of radioactive sources in the well shall not be planned. If the radioactive source cannot be removed, it shall be abandoned in a prudent manner."

To elaborate this, the guidelines state that in order to fulfil the requirements relating to well barriers and securing of wells, Chapters 4.2.1, 4.2.3, 9, and 15 in the NORSOK D-010 standard should be used in the area of HSE [15].

The guidelines are not legally binding, so the NORSOK D-010 standard is not legally binding either, but it provides suggestions and recommendations for technical solutions, and should be used as a minimum standard in order to fulfil the functional requirements of the regulations. Most of the petroleum companies have their own company standards based on international or national standards such as the NORSOK standards as minimum requirements.

4 NORSOK D-010

International standards (ISO, API etc.) form the basis of all activities in the petroleum industry. However, Norwegian safety framework and climate conditions may require own standards in some areas, or additions and supplements to the international standards. To fulfil these needs, the Norwegian petroleum industry, through The Norwegian Oil Industry Association (OLF), has developed the NORSOK standards. OLF supports the preparation and publication of the NORSOK standards, which are managed and issued by Standards Norway [24].

The NORSOK D-010 "Well Integrity" standard defines the minimum functional and performance oriented requirements and guidelines for well design, planning, and execution of safe well operations [24]. The most important chapters regarding P&A operations are Chap. 4.2, 9, and 15. Chapter 4.2 defines the general principles relating to the well barrier term, Chap. 9 describes the requirements for sidetracks, suspension and abandonment operations, and chapter 15 describes the well barrier acceptance criteria's for 50 Well Barrier Elements (WBE).

4.1 Well Barriers

A well barrier is defined by NORSOK D-010 as "an envelope of one or several dependent WBEs preventing fluids or gases from flowing unintentionally from a formation into another formation or to surface. The well barrier(s) shall be defined prior to commencement of an activity or operation by description of the required WBEs to be in place and specific acceptance criteria" [24].

4.1.1 Well Barrier Schematics

Well Barrier Schematics (WBS) are coloured schematics of the different WBEs that make up the well barrier envelope, and describes the

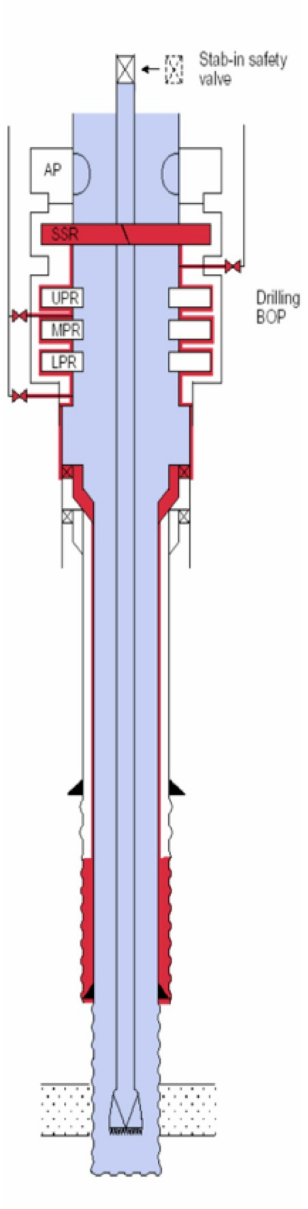
1. primary well barrier in its normal working stage (blue colour)

2. secondary well barrier in its ultimate stage (red colour)

NORSOK recommends WBS to be developed as a practical method to demonstrate and illustrate the presence of the defined primary and secondary well barriers in the well. Figure 4.1 shows an example of a WBS attached in NORSOK.

Example:

5) Drilling, coring or tripping – Shearable drill string



1) **Well barrier elements**	**See Table** *2)*	*3)* **Comments**
Primary well barrier		
1. Fluid column	1	
Secondary wellbarrier		
1. Casing cement	22	
2. Casing	2	Last casing set
3. Wellhead	5	
4. High pressure riser	26	If installed
5. Drilling BOP	4	

4) Note

Legend:

1. *This describes the name of the WBE(s)*
2. *A complete description of general acceptance criteria for this WBE is found in Clause 15 which contains a library of WBE acceptance criteria tables.*
3. *This table column is used to describe comments.*
4. *The place can be used for describing additional requirements and guidelines. For example a description of compensative measures if there exist common WBEs.*
5. *The illustration shows the primary well barrier in its normal working stage, while the secondary well barrier is shown in its ultimate stage. This stage often described with a closed shearing device.*

Figure 4.1: Example of a well barrier schematic [24].

In addition, NORSOK lists a number of typical abandonment scenarios (Table 4.1), some of which are also attached as WBS in the standard.

Table 4.1: Typical Abandonment Scenarios [24]

Item	Description	Comments	See WBS in NORSOK
1.	Temporary abandonment – Non-perforated well.	Non-completed well	9.8.1
2.	Temporary abandonment – Perforated well with BOP or production tree removed.	With well completion installed.	9.8.2
3.	Permanent abandonment – Open hole.		9.8.3
4.	Permanent abandonment – Perforated well.		9.8.4
5.	Permanent abandonment – Multibore with slotted liners or sandscreens.	Covers permanent zonal isolation of multiple reservoirs.	9.8.5
6.	Permanent abandonment – Slotted liners in multiple reservoirs.	Applies also to slot recovery/ side tracks, etc.	9.8.6
7.	Suspension – Hang-off/disconnect of mariner riser.	Hang-off drill pipe.	9.8.7

4.1.2 Well Barrier Acceptance Criteria

In order to qualify the well barrier for its intended use, some requirements called Well Barrier Acceptance Criteria (WBAC) have been developed. This includes requirements relating to number, function, positioning, materials, and verification of the well barrier. NORSOK states that “There shall be one well barrier in place during all well activities and operations, including suspended or abandoned wells, where a pressure differential exists that may cause uncontrolled cross flow in the wellbore between formation zones. There shall be two well barriers available during all well activities and operations, including suspended or abandoned wells, where a pressure differential exists that may cause uncontrolled outflow from the borehole/well to the external environment” [24].

The function of the well barrier and WBE shall be clearly defined, and NORSOK provides a table of all well barriers for P&A operations, and the functions they are intended to fulfil in abandonment scenarios, shown in Table 4.2.

Table 4.2: P&A Well Barrier Functions and Purpose [24]

Name	Function	Purpose
Primary well barrier.	First well barrier against flow of formation fluids to surface, or to secure a last open hole.	To isolate a potential source of inflow from surface.
Secondary well barrier, reservoir.	Back-up to the primary well barrier.	Same purpose as the primary well barrier, and applies where the potential source of inflow is also a reservoir (w/ flow potential and/ or hydrocarbons).
Well barrier between reservoirs.	To isolate reservoirs from each other.	To reduce potential for flow between reservoirs.
Open hole to surface well barrier.	To isolate an open hole from surface, which is exposed whilst plugging the well.	“Fail-safe” well barrier, where a potential source of inflow is exposed after e.g. a casing cut.
Secondary well barrier, temporary abandonment.	Second, independent well barrier in connection with drilling and well activities.	To ensure safe re-connection to a temporary abandoned well, and applies consequently only where well activities has not been concluded.

However, the functions of a well barrier can be combined should it fulfil more than one of the abovementioned objectives, with the exception that a secondary well barrier can never be a primary well barrier for the same reservoir. This means that for wells with more than one reservoir, a well barrier between the different reservoirs is required in addition to a primary and secondary barrier for each reservoir. Barriers between reservoirs can also act as primary barriers for the deeper reservoir. And if the shallower set primary barrier for the shallower reservoir is designed to meet the requirements of both reservoirs, it may act as a primary well barrier for the shallower formation, and at the same time as a secondary well barrier for the deeper reservoir formation.

The well barriers shall be designed such that no single failure of well barrier or WBE leads to uncontrolled outflow from the well to the external environment. The primary and secondary well barriers shall to the extent possible be independent of each other without common WBE. However, if a WBE is an element in both the primary and secondary well barrier, NORSOK requires a risk analysis performed, and risk-reducing measures applied to reduce the risk as low as reasonable practicable. Table 4.3 describes risk-reducing measures that can be applied.

Table 4.3: Risk Reducing Measures for WBE Failure [24]

No	Element Name	Failure Scenario	Probability Reducing Measures	Consequence Reducing Measures
Table 2	Casing	Leak through casing and into annulus, with possibility of fracturing formation below previous casing shoe.	None	Cement in the annulus with verified TOC above the section that is common

The position of the well barriers should be as close as possible to the potential source of inflow, and at a depth where the formation fracture pressure is estimated to be larger than the potential internal pressure. This is to avoid fracturing of the formation as a consequence of the barrier placement, which could lead to other leak paths in the formation.

After establishing the well barrier, the final position of the WBE shall be verified.

For testing of the barriers, NORSOK states that after constructing the barrier, WBEs that require activation shall be function tested, and the well barrier envelope integrity and function shall be verified and documented by a leak test of a satisfying differential pressure.

A low-pressure leak test to 1,5 MPa - 2 MPa for 5 minutes should be performed before the high-pressure leak testing. The high-pressure leak test value shall be equal to or exceed the maximum anticipated differential pressure that the WBE will become exposed to. Static leak test pressure shall be observed and recorded for minimum 10 min. The above test values shall not exceed the rated working pressure of any WBE.

The acceptable leak rate shall be zero, unless specified otherwise. For situations where the leak-rate cannot be monitored or measured, the criteria for maximum allowable pressure fluctuation shall be established.

When inflow testing or leak testing from above to verify the integrity of a well barrier is not possible, or when this may not give conclusive results, other means of ensuring proper installation of a well barrier shall be used. Available options are verification through assessment of job planning and actual job performance parameters.

4.1.3 Well Barrier Elements Acceptance Criteria Tables

In Chap. 15 of NORSOK D-010, specific technical and operational requirements and guidelines relating to WBEs are collated in well barrier element acceptance criteria tables (WBEACT) that shall be applicable for all types of activities and operations. Additional requirements and guidelines or deviations to these general conditions, relating to types of abandonment, will be further described in the sections to follow.

The methodology for defining the requirements/guidelines for WBEs is shown in Table 4-4.

Table 4.4: Well Barrier Element Acceptance Criteria Guidelines [24]

Features	Acceptance Criteria	References
A. Description	This describes the WBE in words.	
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 (i.e. drilling fluid, cement), this should describe • 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, • construction requirements for how to actually construct the WBE or its sub-components, and will in most cases only consist of references to normative standards. For WBEs that are already manufactured, the focus should be on selection parameters for choosing the right equipment and how this is assembled in the field.	Name of specific references
D. Initial test and verification	This describes the methods for verifying that the WBE is ready for use after installation in/on the well and before it can be put into use or is accepted as part of well barrier system.	
E. Use	This describes proper use of the WBE in order for it to maintain its function and prevent damage to it 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 it design/selection criteria during use.	
G. Failure modes	This describes conditions that will impair (weaken or damage) the function of the WBE, which may lead to implementing corrective action or stopping the activity/operation.	

4.2 Sidetracking, Suspension, and Temporary Abandonment

Sidetracking

NORSOK requires the original wellbore to be permanently abandoned prior to a side-track/slot recovery.

Suspension

Suspension of operations requires the same number of well barriers as other abandonment activities. However, the need for WBE testing and verification, can be compensated by monitoring of its performance, such as fluid level/pressure development above well barriers. Well fluids may in such cases be qualified as a WBE.

Temporary Abandonment

For temporary abandonment of a well, NORSOK states that the "Integrity of materials used for temporary abandonment should be ensured for the planned abandonment period times two. Hence, a mechanical well barrier may be acceptable for temporary abandonment, subject to type, planned abandonment period, and subsurface environment." For longer temporary abandonment scenarios, degradation of casing body should be considered. If a subsea completed well is planned abandoned for more than one year, the pressure in the tubing and annulus above the reservoir well barrier ("A" annulus) is required to be monitored. If monitoring is not practicable, the alternative may be to install a deep set well barrier plug [24].

4.3 Permanent Abandonment

Permanently plugged wells have to be abandoned with an eternal perspective, and in addition to the primary and secondary barriers, NORSOK states that "the last open hole section of a wellbore shall not be abandoned permanently without installing a permanent well barrier, regardless of pressure or flow potential. The complete borehole shall be isolated" [24]. If the well to be plugged does not contain any formations with flow potential or hydrocarbons, only the surface barrier is required.

For permanent abandonment wells, the wellhead and the following casings shall be removed such that no parts of the well ever will protrude the seabed. Required cutting depth below seabed should be considered in each case, and be based on prevailing local conditions such as soil, seabed scouring, sea current erosion, etc. The cutting depth should be 5 m below seabed. Use of explosives to cut casing is acceptable only if measures are implemented (directed/ shaped charges and upward protection) which reduces the risk to surrounding environment to the same level as other means of cutting casing. No other obstructions related to the drilling and well activities shall be left behind on the sea floor [24].

Multiple reservoir zones/ perforations positioned within the same pressure regime, isolated with a well barrier in between, can be regarded as one reservoir for which a primary and secondary well barrier shall be installed (Figure 4.2) [24].

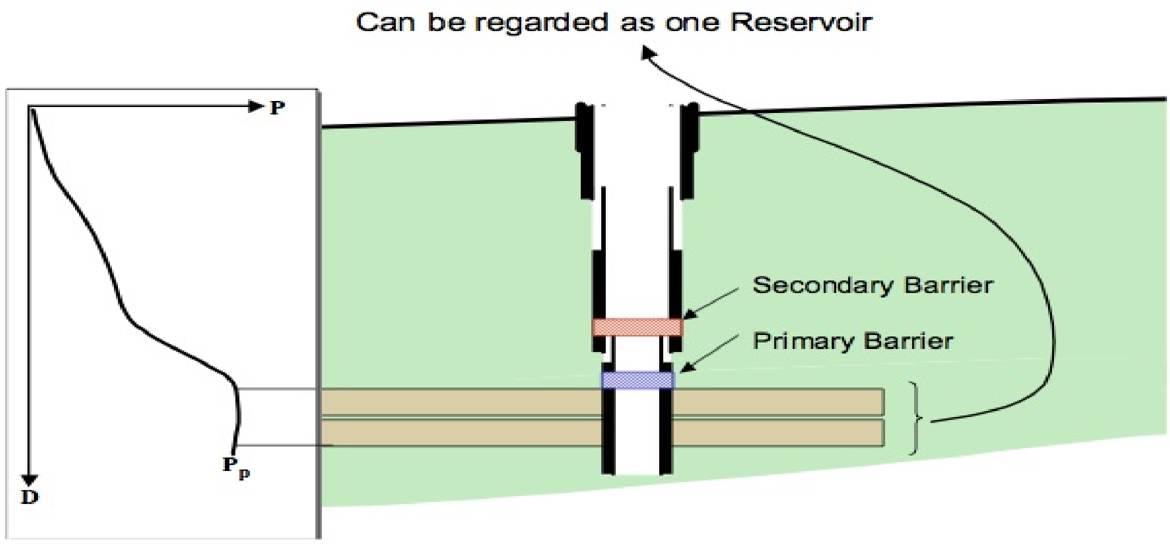


Figure 4.2: Two reservoirs regarded as one [24]

The function of a permanent well barrier is to seal off the permeable formation and avoid all leak paths in all directions. Therefore, permanent well barriers are required to extend across the full cross-section of the well, include all annuli, and seal both vertically and horizontally as seen in Fig. 4.3, sealing both vertically and horizontally [24].

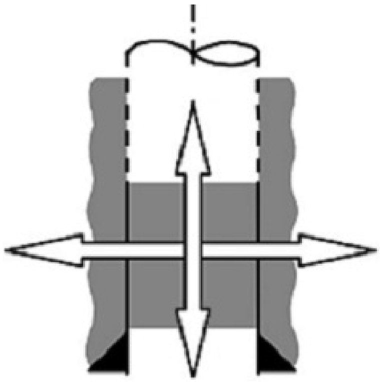


Figure 4.3: Well barrier extending across full cross section of well, sealing both vertically and horizontally [24].

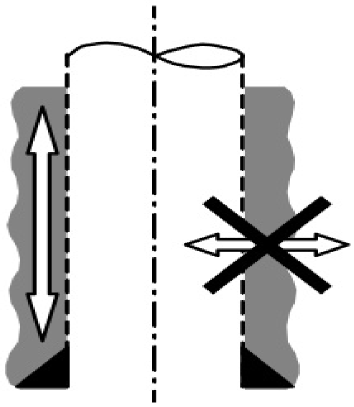


Figure 4.4: Cement in annulus alone not accepted as a permanent WBE, because it is not sealing both vertically and horizontally across the full cross section of the well [24].

Regarding use of casing as a WBE, NORSOK states that steel tubular is not an acceptable permanent WBE unless it is supported by cement, or a plugging material with similar functional properties, both on the inside and outside [24]. A cement plug set inside the casing must therefore be placed at a depth with verified cement, or an equivalent WBE, in all annuli, as seen in Fig. 4.3, sealing both vertically and horizontally across the full cross-section of the well. The presence and pressure integrity of casing cement shall be verified to assess the along hole pressure integrity of this WBE. The cement in annulus alone does not seal both vertically and horizontally across the full cross-section of the well, and will not qualify as a WBE across the well, as seen in Fig. 4.4.

Open hole cement plugs can be used as a well barrier between reservoirs, and is also recommended, as far as practically possible, to be used as a primary well barrier [24].

Cement in the liner lap, unless it has been leak tested from above (before a possible liner top packer has been set) shall not be regarded a permanent WBE [24].

All control cables and lines shall be removed from areas where permanent well barriers are installed, since they may create vertical leak paths through the well barrier. Regarding removal of other downhole equipment, this is not required as long as the integrity of the well barriers is achieved. When well completion tubular are left in the hole and permanent plugs are installed inside and outside the tubular, "reliable methods and procedures to install and verify position of the plug inside the tubular and in the tubular annulus shall be established" [24].

Some of the well barrier acceptance criteria in Chap. 15 of the NORSOK standards need additional requirements to be acceptable as permanent abandonment barriers. These additional requirements are summarized in Table 4.5.

Table 4.5: Additional WBEAC Requirements for Permanent Abandonment Barriers [24]

NORSOK WBEACT reference no	Element name	Additional features, requirements and guidelines
Table 2	Casing	Accepted as permanent WBE if cement is present inside and outside.
Table 22	Casing cement	Accepted as a permanent WBE together with casing and cement inside the casing. Should alternative materials be used for the same function a separate WBEAC shall be developed.
Table 24	Cement plug	Cased hole cement plugs used in permanent abandonment shall be set in areas with verified cement in casing annulus. Should alternative materials be used for the same function a separate WBEAC shall be developed. A cement plug installed using a pressure tested mechanical plug as a foundation should be verified by documenting the strength development using a sample slurry subjected to an ultrasonic compressive strength analysis or one that have been tested under representative temperature and/or pressure.
Table 25	Completion string	Accepted as permanent WBE if cement is present inside and outside the tubing.
Table 43	Liner top packer	Not accepted as a permanent WBE.

4.4 Material Requirements and Desired Properties

Regarding use of materials in P&A operations, NORSOK states that "the materials used in well barriers for plugging of wells shall withstand the load/ environmental conditions it may be exposed to for the time the well will be abandoned. Tests should be performed to document long term integrity of plugging materials used" [24].

For materials used in permanent well barriers, NORSOK defines 6 properties that are desired, but not required [24]:

"A permanent well barrier should have the following properties:

a) Impermeable

b) Long term integrity.

c) Non-shrinking.

d) Ductile – (non-brittle) – able to withstand mechanical loads/impact.

e) Resistance to different chemicals/ substances (H_2S, CO_2 and hydrocarbons).

f) Wetting, to ensure bonding to steel."

NORSOK D-010 is meant to define minimum functional requirements, so it generally tries to avoid specifying material type, and instead defines the functional requirements that the material must fulfil. It does however mention some materials that are not acceptable parts of a permanent well barrier:

"Elastomer seals used as sealing components in WBEs are not acceptable for permanent well barriers" [24].

Because bridge plugs use elastomer seals, these cannot be used as permanent WBEs. However, they can be used to assist the placement of cement plugs. Although cement plugs are usually required by NORSOK to be verified, an exception is made for cement plugs set inside casing on top of a tagged and pressure tested bridge plug. If the bridge plug has already been pressure tested, a new pressure test would not reveal any potential leaks in the cement plug.

4.5 Plug & Abandonment Design

Before planning a permanent P&A, NORSOK gives a number of requirements to which information should be collected as a minimum basis for P&A program design, in addition to the depth and size of the permeable formations [24]:

“The following information should be gathered as a basis of the well barrier design and abandonment program

- Well configuration (original, intermediate and present) including depths and specification of permeable formations, casing strings, primary cement behind casing status, well bores, side-tracks, etc.
- Stratigraphic sequence of each wellbore showing reservoir(s) and information about their current and future production potential, where reservoir fluids and pressures (initial, current and in an eternal perspective) are included.
- Logs, data and information from primary cementing operations in the well.
- Estimated formation fracture gradient.
- Specific well conditions such as scale build up, casing wear, collapsed casing, fill, or similar issues.“

For well barriers consisting of cement, NORSOK describes a few considerations regarding uncertainties that should be accounted for in the cement slurry design “relating to

- downhole placement techniques,
- minimum volumes required to mix a homogenous slurry,
- surface volume control,
- pump efficiency/ -parameters,
- contamination of fluids,
- shrinkage of cement. “

Regarding load cases the well barrier shall be designed for, NORSOK describes a few requirements summarized in Table 4.6. The specific gravity of well fluids accounted for in the design for permanently abandoned wells, shall maximum be equal to a seawater gradient [24].

Table 4.6: Load Cases for Well Barrier Design [24]

Item	Description	Comments
1.	Minimum depth of primary and secondary well barriers for each reservoir/potential source of inflow, taking the worst anticipated reservoir pressure for the abandonment period into account.	Not shallower than formation strength at these depths. Reservoir pressure may for permanent abandonment revert to initial/virgin level.
2.	Leak testing of casing plugs.	Criteria as given in Table 24.
3.	Burst limitations on casing string at the depths where abandonment plugs are installed.	Cannot set plug higher than what the burst rating allows (less wear factors).
4.	Collapse loads from seabed subsidence or reservoir compaction.	The effects of seabed subsidence above or in connection with the reservoir shall be included.

Minimum Design Factors

The minimum design factors for burst, collapse, tension, and tri-axial loads shall be the same as described in the NORSOK chapters for drilling and completion activities.

4.6 Specific Cement Barrier Requirements

In Chap. 15 of the NORSOK requirements, there are attached more than 50 WBEACT. The most relevant to P&A are Table 4.7 for a Cement plug (Table 24 in NORSOK) and Table 4.8 for Casing Cement (Table 22 in NORSOK). These tables describe the specific technical and operational requirements and guidelines for a cement plug and cement behind casing used as WBE.

Cement Plug Requirements

For a cement plug, NORSOK states that the WBE is described as cement in its solid state, and that the purpose is to prevent flow of formation fluids between formation zones and/or to surface/seabed. Regarding design, construction, and selection, there are 9 requirements including a cementing program and a minimum cement batch volume to make homogenous slurry and avoid contamination. The table also refers to the API standard 10A class 'G' cement for qualification and properties requirements. There are also a few requirements regarding the length of the plug. It shall be at least 100 m measured depth (MD), unless it is set inside a casing with a mechanical plug as a foundation, then the minimum length is 50 m MD. The plug shall also extend minimum 50 m MD above any source of inflow/leakage point. A plug in transition from open hole to casing should extend at least 50 m MD below casing shoe. NORSOK also states that a casing/ liner with shoe installed in permeable formations should have a 25 m MD shoe track plug [24].

Regarding testing and verification of the cement plug, the WBEACT states that the plug shall be tested and verified through tagging and leak tests with pressures of which ever is lower of 7000 kPa ($\sim$1000 psi) above estimated formation strength below casing/ potential leak path, or 3500 kPa ($\sim$500 psi) for surface casing plugs, and not exceed casing pressure test, less casing wear factor. If a mechanical plug is used as a foundation for the cement plug, and this is tagged and pressure tested, the cement plug does not have to be verified, because the leak test would not show any different results than the mechanical plug anyhow [24].

Table 4.7: WBEACT for Cement Plug [24]

<table>
<tr><th>Features</th><th>Acceptance Criteria</th><th>References</th></tr>
<tr><td>A. Description</td><td>The element consist of cement in solid state that forms a plug in the wellbore</td><td></td></tr>
<tr><td>B. Function</td><td>The purpose of the plug is to prevent flow of formation fluids inside a wellbore between formation zones and/or to surface/seabed.</td><td></td></tr>
<tr><td>C. Design, construction and selection</td><td>1. A design and installation specification (cementing program) shall be issued for each cement plug installation.
2. The properties of the set cement plug shall be capable to provide lasting zonal isolation.
3. Cement slurries used in plugs to isolate permeable and abnormally pressured hydrocarbon bearing zones should be designed to prevent gas migration.
4. Permanent cement plugs should be designed to provide a lasting seal with the expected static and dynamic conditions and loads down hole.
5. It shall be designed for the highest differential pressure and highest downhole temperature expected, inclusive installation and test loads.
6. A minimum cement batch volume shall be defined for the plug in order that homogenous slurry can be made, to account for contamination on surface, downhole and whilst spotting downhole.
7. The firm plug length shall be 100 m MD. If a plug is set inside casing and with a mechanical plug as a foundation, the minimum length shall be 50 m MD.
8. It shall extend minimum 50 m MD above any source of inflow/ leakage point. A plug in transition from open hole to casing should extend at least 50 m MD below casing shoe.
9. A casing/ liner with shoe installed in permeable formations should have a 25 m MD shoe track plug.</td><td>API Standard 10A Class ‘G’</td></tr>
<tr><td>D. Initial test and verification</td><td>1. Cased hole plugs should be tested either in the direction of flow or from above.
2. The strength development of the cement slurry should be verified through observation of representative surface samples from the mixing cured under a representative temperature and pressure.
3. The plug installation shall be verified through documentation of job performance; records fm. cement operation (volumes pumped, returns during cementing, etc.).
4. Its position shall be verified, by means of:
<table>
<tr><th>Plug type</th><th>Verification</th></tr>
<tr><td>Open hole</td><td>Tagging, or measure to confirm depth of firm plug</td></tr>
<tr><td>Cased hole</td><td>Tagging, or measure to confirm depth of firm plug Pressure test, which shall
1. Be 7000 kPa (∼1000 psi) above estimated formation strength below casing/ potential leak path, or 3500 kPa (∼500 psi) for surface casing plugs, and
2. not exceed casing pressure test, less casing wear factor which ever is lower. If a mechanical plug is used as a foundation for the cement plug and this is tagged and pressure tested the cement plug does not have to be verified.</td></tr>
</table></td><td></td></tr>
<tr><td>E. Use</td><td>Ageing test may be required to document long term integrity</td><td></td></tr>
<tr><td>F. Monitoring</td><td>For temporary suspended wells: The fluid level/ pressure above the shallowest set plug shall be monitored regularly when access to the bore exists.</td><td></td></tr>
<tr><td>G. Failure modes</td><td>Non-compliance with above mentioned requirements and the following:
• Loss or gain in fluid column above plug.
• Pressure build-up in a conduit which should be protected by the plug.</td><td></td></tr>
</table>

Casing Cement Requirements

For cement used as a barrier behind casing, some of the requirements are the same as for a plug, but there are also some requirements that differ, as we can see from Table 4.8.

For cement design, the requirements vary with different casings as well. While the general requirement is 100 m length of cement, some casing cements have special requirements, or are not acceptable as WBE. For cemented casing strings in hydrocarbon formations, which are not drilled out, the requirements are stricter than for the cement plug. The height above a point of potential inflow / leakage point / permeable formation with hydrocarbons, shall be 200 m, or to previous casing shoe, whichever is less. The casing cement should also be designed to withstand temperature exposure and temperature cycling over time. Design requirements reference is also made to the international standard ISO 10426-1 [24].

The cement behind casing shall be verified through formation strength tests when the casing shoe is drilled out, or by exposing the cement column for differential pressure from fluid column above cement in annulus. The TOC shall be verifies by either logging or estimated by calculations based on records from the cement operation. The strength development shall be verified by observation of representative samples from the mix cured under representative pressure and temperatures. The annuli pressure above cement shall also be monitored when access to the annulus exists [24].

Table 4.8: WBEACT for Casing Cement [24]

Features	Acceptance Criteria	References
A. Description	This element consists of cement in solid state located in the annulus between concentric casing strings, or the casing/liner and the formation.	
B. Function	The purpose of the element is to provide a continuous, permanent and impermeable hydraulic seal along hole in the casing annulus or between casing strings, to prevent flow of formation fluids, resist pressures from above or below, and support casing or liner strings structurally.	
C. Design, construction and selection	1. A design and installation specification (cementing program) shall be issued for each primary casing cementing job. 2. The properties of the set cement shall be capable to provide lasting zonal isolation and structural support. 3. Cement slurries used for isolating permeable and abnormally pressured hydrocarbon bearing zones should be designed to prevent gas migration. 4. The cement placement technique applied should ensure a job that meets requirements whilst at the same time imposing minimum overbalance on weak formations. ECD and the risk of lost returns during cementing shall be assessed and mitigated. 5. Cement height in casing annulus along hole (TOC): **5.1 General:** Shall be 100 m above a casing shoe, where the cement column in consecutive operations is pressure tested / the casing shoe is drilled out. **5.2 Conductor:** No requirement as this is not defined as a WBE. **5.3 Surface casing:** Shall be defined based on load conditions from wellhead equipment and operations. TOC should be inside the conductor shoe, or to surface/seabed if no conductor is installed. **5.4 Casing through hydrocarbon bearing formations:** Shall be defined based on requirements for zonal isolation. Cement should cover potential cross-flow interval between different reservoir zones. For cemented casing strings which are not drilled out, the height above a point of potential inflow / leakage point / permeable formation with hydrocarbons, shall be 200 m, or to previous casing shoe, whichever is less. 6. Temperature exposure, cyclic or development over time, shall not lead to reduction in strength or isolation capability. 7. Requirements to achieve the along hole pressure integrity in slant wells to be identified.	
D. Initial test and verification	• The combined element consisting of material and foundation shall be verified through formation strength test when the casing shoe is drilled out. Alternatively, the verification may be performed through exposing the column for differential pressure from fluid column above the material in the annulus. In the latter case the pressure acceptance criteria and verification requirements shall be defined. • The verification requirements for having obtained the minimum height shall be described, which can be - verifications by logs (gravel pack evaluation, bond log), and/or - estimation on the basis of records from the pumping operation (volumes pumped, returns during pumping, etc.). • Properties of each batch of material produced shall be verified by laboratory testing to be within accepted values for density and water content to ensure sealing capability. This shall be documented in the batch certificate issued by the manufacturing plant.	
E. Use	None	
F. Monitoring	1. The annuli pressure above the well barrier shall be monitored regularly when access to this annulus exists. 2. Surface casing by conductor annulus outlet to be visually observed regularly.	
G. Failure modes	Non-fulfilment of the above requirements (shall) and the following: 1. Pressure build-up in annulus as a result of e.g. insufficient volumes placed in the well, excessive contamination of the material during placement, etc.	

4.7 Other Topics

NORSOK also addresses a few other topics not directly related to barrier and material requirements. However, these topics are also important parts of the P&A operations standards.

Well Control Action Procedures and Drills

NORSOK describes a few well control action procedures that should be available to deal with incidents, such as trapped gas in casing annulus, when cutting of casing, or pulling casing hanger seal assembly, if these incidents should occur. Additional scenarios may be applied dependent on the planned activity.

There is also a description of well control action drills that should be performed, including pressure-build-up, or lost circulation in connection with a cutting of casing operation, and loss of well barrier whilst performing an inflow test. These well control action drills should be performed to verify the crew response in applying correct well control practices.

Risks

Risk shall be assessed relating to time effects on well barriers such as long term development of reservoir pressure, possible deterioration of materials used, sagging of weight materials in well fluids, etc. HSE risks related to removal and handling of possible scale in production tubing shall be considered in connection with plugging of development wells. HSE risk relating to cutting of tubular goods, detecting and releasing of trapped pressure, and recovery of materials with unknown status shall also be assessed [24].

5 Well Plugging Materials

Plugging materials are the materials used to isolate permeable zones from each other and/or from the surface when suspending or abandoning a well. These materials need to be strong, pumpable, long lasting, and of extremely low permeability to be good isolation materials. Through the years, cement has been the dominating plugging material used almost exclusively. However, during the last 10-15 years, a few new alternative materials have been developed, among them ThermaSet and Sandaband.

5.1 Cement

Oilfield cements can vary in complexity and properties, but are usually based on Portland cement (PC) [7], which is the most widely used cement in the world [21]. When dry cement is mixed with water, the cement sets and develops strength through a chemical exothermic reaction between the water and the compounds present in the cement. This reaction is called hydration, and the development of strength is predictable, uniform, and relatively rapid. After hydration, the set cement will harden into a solid impermeable mass, well suited for zonal isolation in P&A operations [7].

5.1.1 API Cement Classification System

Because different types of PC are used in different depths and environments, the American Petroleum Institute (API) has developed a classification system widely used in the petroleum business [7]. There are eight classes of PC, designated A to H. They are arranged according to the depth that they are placed, and the temperatures and pressures they are exposed to.

Table 5.1: API Classification System [7]

API class	Description
Class A	Intended for use from surface to depth of 6000 ft (1,830 m) when special properties are not required.
Class B	Intended for use from surface to depth of 6000 ft (1,830 m) when conditions require moderate to high sulfate resistance. Has lower C3A content than Class A.
Class C	Intended for use from surface to depth of 6000 ft (1,830 m) when conditions require high early strength. Available in all three degrees of sulfate resistance. Has a high C3S content and surface area.
Class D	Intended for use at depths from 6000 ft (1,830 m) to 10,000 ft (3,050 m) under conditions of moderately high temperatures and pressures.
Class E	Intended for use at depths from 10,000 ft (3,050 m) to 14,000 ft (4,270 m) under conditions of high temperatures and pressures.
Class F	Intended for use at depths from 10,000 ft (3,050 m) to 16,000 ft (4,880 m) under conditions of extremely high temperatures and pressures.
Class G	Intended for use as a basic well cement foam.
Class H	Intended for use from surface to depth of 8,000 ft (2,440 m) as manufactured, but can be used with accelerators and retarders to cover a wide range of well depths and temperatures.

5.1.2 Cement Problems and Challenges

Even though cement is the most widely used plugging material, and we have great experience through many years of using it, cementing is still one of the most challenging operations to ensure high quality. Most of the problems and challenges of cement comes with the hydration process and the fact that cement needs time to cure and become a solid tight material. During this curing time, there is a number of ways in which the cement can fail [2]. While the cement slurry is liquid, it is important to maintain a sufficient hydrostatic pressure, to avoid influx of gas or liquids that could contaminate the slurry and change the properties the slurry was designed to have. It is also important to maintain a low enough density to avoid volume losses, which could lead to an inaccurate and unacceptable cement placement and length. Other problems during curing time include premature gelation, cement shrinkage, and poor bonding to formation/casing. Another problem is poor hole cleaning before cementing. If channels of mud remain in the annulus, the lower yield stresses of drilling fluids may offer a preferential route for gas migration. Also, water may be drawn from the mud channels when they come into contact with cement. This can lead to shrinkage induced cracking of the mud, which also provides a route for gas to flow [2].

After years and years of being exposed to loads, the cement could also fail caused by stresses and/or geological changes. Cement is a brittle material that may crack and fracture if exposed to large enough stresses.

Maintaining long-term barrier integrity in P&A operations is critical. A failed cement barrier may lead to catastrophic consequences. That is why it is extremely important to deal with these challenges even in the early days of planning and design.

Special Environments

Some special environments require extra focus on specific challenges in these environments:

High temperature variations: In high pressure / high temperature (HPHT) formations, steam injected wells, and some places in the arctic, the wells are subjected to high temperature variations and these changes affect both the formation and the casings, causing expansion and contraction. This expansion and contracting of casing and plastic formation like salt causes cracks in the already set cement [32].

Permafrost: Some places in the arctic we have permafrost, which can be challenging to cement because of freezing of mix-water before the cement sets, development of cracks resulting from the freezing of water in the capillaries of the cement, and thawing of the permafrost caused by the heat released during the exothermic process of cement hydration. If the permafrost contains gas hydrates, they can decompose to release methane in dangerous quantities [5].

Corrosive environments: In some environments, the cement must also withstand corrosive attacks from aggressive formation and/or injection fluids, such as in CO_2 flooding for enhanced oil recovery or in CO_2 capture and storage wells.

Cementing Horizontally

Horizontal wells are particularly challenging regarding some issues, and needs extra focus on some slurry properties. Two of the most important properties in horizontal wells are slurry stability and fluid loss [7].

Slurry stability depends on two things; free water content and sedimentation. The free water can migrate to the upper side of the wellbore and create a channel, which fluids can flow (Figure 5.1). Sedimentation can result in low-strength, highly porous cement in the upper part of the hole. This can result in fluid migration and loss of zonal isolation. To avoid this, free water should be maintained at zero, and adding of thickening agents should be considered.

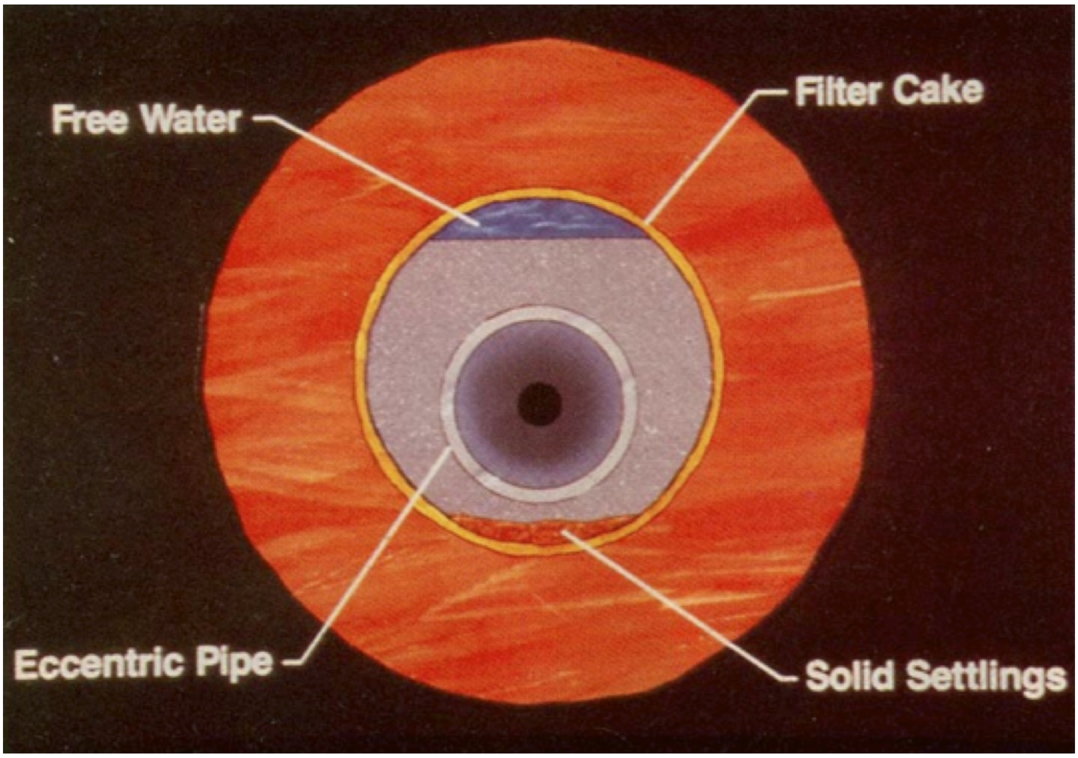


Figure 5.1: Cementing problems in horizontal wells [18]

Fluid-loss control is important because the long permeable sections the cement slurry is exposed to in horizontal wells, is more extensive than in vertical wells. Low fluid loss is very important to maintain the desired properties of the slurry.

5.1.3 Cement Additives

Cement intended for permanent P&A must be designed to perform at different temperatures and pressure ranges, develop sufficient strength, maintain the required strength in an eternal perspective, and have properties to avoid cement setting problems. Different cement additives make it possible to modify cement properties into an optimized cement slurry mix. Today, there exist more than 100 additives for well cementing, and we can divide them into eight major categories used in well cementing [7].

- Accelerators: Chemicals that shorten the setting time of the cement slurry and accelerates the rate of compressive strength development.
- Retarders: Chemicals that increases the setting time of cement.
- Extenders: Materials that lower the density of the cement and may reduce the quantity of cement per unit volume of set product.
- Weighting agents: Materials that increase the cement density.
- Dispersants: Chemicals that reduce the viscosity of a cement slurry.
- Fluid loss control agents: Materials that control leakage of the aqueous phase of a cement system to the formation.
- Lost circulation control agents: Materials that control loss of the cement slurry to weak formations.
- Specialty additives: miscellaneous additives, such as antifoam agents, fibers, etc.

5.1.4 Special Cement Systems

While the technology of well cementing has advanced, problems as described in Sec. 5.1.2, have been encountered for which special cement systems have been developed [7]. Examples of such special cement systems are gathered in Table 5.2.

Table 5.2: Special Cement Systems

Environment/Conditions	Cement System	Comments
Weak zones / Lost circulation problems	Thixotropic cement systems	Rapid development of gel strength
Permafrost zones	Calcium-aluminate	Sets and gains strength rapidly
Permafrost zones	Gypsym-cement blends	Gypsum phase sets rapidly and protects PC setting
Salt formations / Water sensitive formations	Salt cement systems	Significant amount of sodium chloride or potassium chloride
Corrosive environments	Epoxy cements	Epoxy resin mixed with hardening agent
HPHT wells	Thermal cements	Reduced lime-silica ratio (C/S)
Fractured formations / Formations with low fracture gradient	Foam cement	Cement with nitrogen gas quality up to 40% enables density as low as 4 lbm/gal

5.1.5 Testing, Qualification, and Certification

Earlier, the most widely used cement class for P&A operations was API class E and F, but the last 20 years, API class G has dominated cement plugs around the world. In Norway, Norcem produces most of the oilwell cement used in Norwegian wells. Norcem started producing oilwell cements in 1972, right after the Norwegian oil adventure started. The last 5 years, their factory in Brevik in Norway had a yearly production of this special cement, called Norwell, of approximately 30-35 000 tons [9]. There exist different variations of Norwell, mixed with additives, produced for different environments and job descriptions.

Norcem is an API certified oilwell cement producer, certified to produce API class G cement. This certification means that the produced cement fulfils the requirements stated in the API Standard 10A class "G". The test certificate is attached as Appendix C.

5.1.6 Areas of Use

Traditionally, cement is the material used for all P&A operations. This is also one of the main advantages of cement – the industry has enormous experience in plugging wells with cement. Cement is a very complex material, it can be modified to have almost any desired property, but it also has several ways of failing as described in the previous sections. Cement can be used in permanent P&A as well as temporary P&A, suspension, and as a base for sidetracks. It can be used in all P&A operations, from primary cementing to reservoir plugs, remedial squeeze cementing, and the top surface plug. It can be modified by additives to operate in different environments, regarding everything from different pressures to different temperatures and chemical exposure. The ability to modify the cement design for different environments is probably the most important reason that cement will still be the foundation and most common plugging material also in the future.

5.2 ThermaSet®

ThermaSet is a resin-based sealant that sets when it is exposed to a pre-determined temperature for a certain amount of time [30]. In its liquid form, ThermaSet can easily be pumped and injected into small openings such as control lines, because it contains no particles in its neat form. However, particles are normally used to accurately adjust the density from less than 5.8 lbm/gal up to approximately 21 lbm/gal. Other properties, like viscosity and curing time can also be accurately regulated. Compared to cement, ThermaSet has advantages when it comes to mechanical strength. ThermaSet has a higher compressive strength than cement, and also significantly higher tensile strength – approximately 60 times higher than cement. Along with approximately 5 times higher flexural strength, this makes ThermaSet better suited for varying loads than cement. These varying loads could be caused by pressure and temperature cycles that cause the casing to expand and contract, exerting a force on the annulus material.

5.2.1 Testing, Qualification and Certification

31 different qualification tests have been completed on ThermaSet to qualify it as a plugging material [30]. Among those tests, ThermaSet has been tested and qualified according to ISO 14310 V3. This is a liquid penetration test that includes axial loads and temperature cycling. The gas tightness of ThermaSet has been tested satisfactory gas-tight by Proserv in a 5000psi nitrogen test [29]. SINTEF has performed tests to document the mechanical properties, with the results shown in Table 5.3.

Table 5.3: ThermaSet Mechanical Properties Test Results [30]

Properties	ThermaSet	Portland class G"cement
Compressive strength (MPa)	77 ± 5	58 ± 4
Flexural strength (MPa)	45 ± 3	10 ± 1
E-Modulus (MPa)	2240 ± 70	3700 ± 600
Rupture Elongation (%)	3.5	0.01
Failure flexural strain (%)	1.9 ± 0.2	0.32 ± 0.04

These results show that ThermaSet performs even better than conventional cement in almost every aspect. The Compressive strength and Flexural Strain is exceedingly stronger than that of Portland G cement, the E-modulus show a far superior elasticity, and a highly increased Compressive Strength is demonstrated.

SINTEF also performed an Ageing Test to document long-term integrity of ThermaSet. The test showed that reservoir conditions have some impact on ThermaSet in a long-term perspective, but the mechanical strength reduction seem to flatten out after a while, and are still satisfactory (over 50% of initial strength). The permeability was also shown to remain low over time. During the Ageing Test, a component in ThermaSet was shown to have issues with H_2S, but this component was not needed, and have now been removed from the design [23].

5.2.2 Areas of Use

ThermaSet can be used in many of the same areas as cement, even as primary casing cementing. ThermaSet has about 5 times the bonding strength to steel as class G"cement, and is therefore a strong alternative to cement regarding casing support. It has already been used as casing support in Saudi Arabia, where the mechanical properties was critical for choosing ThermaSet.

ThermaSet may also beneficially be used as fill behind casing above the primary cement for zonal isolation and preparation for future abandonment. Either pumped in front of the cement, pumped on the outside of the casing, or squeezed through perforations in the casing. ThermaSet could especially be a very good solution in squeeze plugging, because of its properties as a liquid. The low viscosity and low content of solids makes it easy to pump through small perforations. This advantage could also be used to fix leaking cement plugs with cracks or microannulus.

For deviated/horizontal plugging, ThermaSet also appears as a better solution, because of its uniform resin appearance. Gravity will not affect the placement and quality of ThermaSet the same critical way as for cement.

However, the most important area of use for ThermaSet would be in wells with especially challenging conditions. In wells with high temperature variations, like HPTH-, arctic-, steam injection-, and geothermal wells, ThermaSet seems like the best plugging material, because of its high strength, both compressive-, and tensile strength.

5.3 Sandaband

According to Sandaband Well Plugging [19], Sandaband is an incompressible, everlasting gas-tight material. It is liquid as pumped and solid at rest. Further, it is non-shrinking, non-fracturing, non-segregating, thermodynamically stable, and chemically inert [19]. It is also environmentally safe, has no health hazards, and is non-damaging to the reservoir. But one of the problems is that the material needs a solid base to be placed on – if it is placed on top of a fluid it will sink. This can be solved with assistance of either a mechanical plug, or another plugging material as a base.

Figure 5.2: Sandaband [19]

Sandaband consists of up to 85% quartz solids with a grain size diameter varying from less than a micrometre to a couple of millimetres. The rest of the volume consists of water and chemicals controlling the liquid properties like viscosity and freezing temperature. The quartz particles are kept together by electrostatic forces (Zeta bindings) between the water molecules and the surface of the smallest micro-silica grains, and hinder flow in the pore spaces [27].

The permeability in Sandaband is dependent on the sorting and packing of the different sized particles [26]. If an optimized mix of different sized particles are carefully mixed and packed in an optimized, tight, dispersed way – redistribution or sorting of the particles after placement is minimal, because of the packing and the Zeta-bindings preventing all particle movement relatively to each other. Sandaband has been tested to 5G without segregation [19]. The permeability is also dependent on the saturation and viscosity of the fluid, which can be controlled by chemical additives. The permeability is therefore possible to manipulate and adjust according to desired properties for the particular well conditions.

Sandaband does not set up following a chemical reaction, and therefore requires no setting time, like cement does. Instead, Sandaband has properties like a Bingham Plastic material. Bingham Plastic liquids are characterized by the fact that they need a certain minimum initial shear stress to start flowing, but have a linear relationship between shear stress and shear strain, as seen in Figure 5.3.

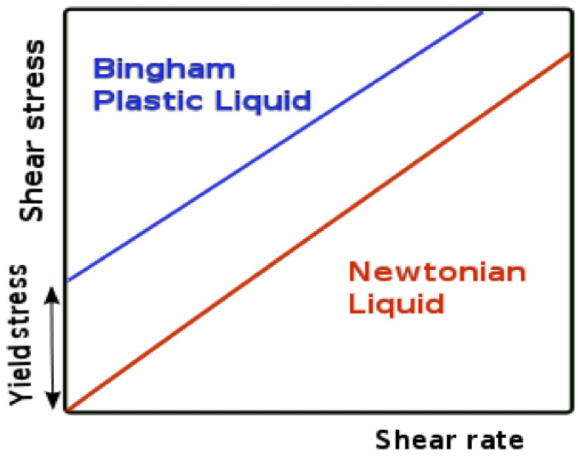


Figure 5.3: Bingham plastic behaviour [31]

This process is not time-dependent; meaning that the slurry will rapidly form a rigid body when pumping is stopped, and can be pumped away like a liquid when re-starting the pumps. Also, if the well experiences dynamic loads that cause stresses in the material, Sandaband will deform and conform to the surroundings instead of cracking and fracturing like a brittle material would. If a cap is needed to ensure the placement and protect Sandaband, it could be used in combination with another plugging material on top.

Another advantage of this Bingham plastic material behaviour is that Sandaband has close to zero losses to the formation. When Sandaband enters potential fractures in the formation, it increases its area, and the shear stress needed to move the fluid increase, until Sandaband has filled the fracture openings and sets like a solid again. The low loss to formation makes the needed volume of Sandaband easy to calculate, and it becomes easier to place a successful plug.

There are two factors that influence how much pressure a Sandaband plug can control. First of all, the hydrostatic pressure created by the fluid column, and secondly, the yield point of the Bingham Plastic material, which gives a pressure seal dependent on the contact area between the plug and the borehole wall. This can be compared to a friction force, because it works in the opposite direction of the experienced force, preventing the plug from moving until the yield stress is exceeded.

One of the main disadvantages of Sandaband is the fact that it needs to be pre-mixed onshore. This could cause problems regarding uncertainties in volume requirements. The advantage though, is that Sandaband experiences almost zero losses to the formation, caused by its behaviour as a Bingham Plastic material, so volumes should be easier to predict.

Another difference from cement is verification of plug placement. Verification of the top of sand slurry is slightly different from verification of top of cement. A cement plug placement and condition would have been verified after curing by tagging with the correct weight, by use of the drill pipe. This is not possible with the concentrated sand slurry because of its behaviour as a Bingham plastic material. Therefore, placing the bottom of the drill string at the planned top of sand slurry and circulating bottoms up, while observing the returns, provides verification of correct placement. If sand is observed over the shakers, this verifies that Sandaband is present at the given depth [19].

However, if the material is placed in the annulus, neither Sandaband nor other materials can be verified by use of the mentioned techniques. Both Sandaband and cement in the annulus may be evaluated by use of logging tools, although not necessarily the same types of logging tools. While several tools may be used, the preferred method of logging Sandaband is by use of a pulsed neutron tool. These contain a high-energy neutron generator that emits neutrons that are bombarded onto the formation. The different nuclei in the formation then interact with the incoming neutrons and start radiating gamma rays. Analysis of the energy spectra can separate different elements, such as the silicon, which is abundant in quartz. Because quartz is the main component in Sandaband, its presence can then be identified [20].

Other methods of verification, like pressure testing and observing operational parameters, are done in much the same way as with cement. As long as the design parameters for the plug are not exceeded, pressure testing and inflow testing can be performed straight after the plug has been placed, because there is no setting time involved.

5.3.1 Testing, Qualification and Certification

The gas-tightness of Sandaband has been documented by use of the Intertek JVS 1000 test, which is the recommended test for gas-tight cement slurries on the NCS [17]. Sandaband has also been long-term integrity tested in the temperature range -10°C to 250°C [27].

Sandaband has also been tested for casing moving and vibration effects on the gas-tightness, with results of no effect on the gas-tightness [19]. This is to prove the capability for the Sandaband to deform and adapt to the changing conditions/loads, proving the properties of a ductile material. There have also been performed self-healing tests, where repeated break-through is forced, and the self-healing capabilities are shown [19].

Also, a third-party report was made by Proffshore to verify that Sandaband fulfils the material requirements for permanent plugging in NORSOK. This report concluded positively on Sandabands compliance as a permanent WBE, but underlined the need for a sufficient height and length to control required pressure. Because cement can set up to form a solid plug, the hydraulic sealing properties are not as dependent on height and length as Sandaband, meaning that a longer plug may be necessary if Sandaband is used compared to cement.

5.3.2 Areas of Use

No required setting time, which saves time, money and eliminates setting time problems, makes Sandaband a good solution in different scenarios. However, the need for a solid base limits this use to reservoir plugging, and plugging in combination with a mechanical plug or another plugging material. Combinations with mechanical plugs may not be optimal, as mechanical plugs are not accepted as permanent barriers, and could fail in a long-term perspective. If a mechanical plug foundation should fail, the Sandaband plug on top may sink and re-position itself, and therefore not provide the same level of safety anymore. In addition, the need for a hydrostatic head does not make Sandaband well suited for use in highly deviated and horizontal wells.

Sandaband with its properties for zero losses is a perfect plugging material for zones with challenges regarding heavy losses. This also makes Sandaband a very good material for fill behind casing to act as a barrier in the annulus. But again, because it is not self-supporting, it needs to be placed on top of a solid foundation.

The ability to be circulated makes Sandaband a perfect material for temporary reservoir plugging. It has an advantage in re-entering the reservoir at a later stage, because the Sandaband plug simply can be washed away and thus no milling or drilling time is needed.

In corrosive environments like CO_2 injection wells or wells drilled through salt formations, Sandaband seems like a very good alternative to cement, because it does not react with any chemicals.

6 Discussion

As mentioned in Chap. 3 and 4, NORSOK D-010 is not legally binding on the NCS, but it is recommended as a minimum standard regarding HSE. This recommendation makes the document important to ensure safety and quality on the NCS. Most of the companies operating on the NCS use this standard as a base for their company standards that apply for all their operations. An important document like this should be frequently revised and kept up to date with technological development, as the industry changes the game and improves continuously. While more and more challenging environments and conditions are to be explored, the industry depends on technological improvements, and the regulations and HSE requirements must adapt and keep up with this development.

NORSOK D-010 was last revised in August 2004. This is almost 8 years ago. The next revision has been announced and the work has already started, but it seems like it will not be finished until late 2012. When it comes to P&A technology, the industry has improved a lot the last 8 years. More and more wells have finished their producing life and needs to be abandoned. P&A as a part of the wells life, has traditionally not been given a lot of focus, but the fact that P&A is a costly operation combined with the increasing number of old wells, has lately led the industry to put more interest and focus into technology development in this area. The technology is always moving towards a safer, cheaper, more efficient, and better solution than before. To be able to keep up with the technology development and maintain the benefits of having standards for the newest technology solutions, the industry standards should be revised more frequently than every 8 years, as the case for NORSOK D-010 is now. This would improve the overall safety level, in addition to avoiding radical adjustments to the standards, by adjusting and making sure the standards are up to date more frequently. A revision every 2 or 3 years is recommended to avoid gaps between technology improvements and the requirements in the standards.

NORSOK D-010 is a standard created by the industry itself, and naturally it will focus on the material being used for P&A at the time of the document revision. Traditionally, cement has been the preferred material, used almost exclusively in P&A operations. This is clearly reflected in NORSOK, where parts of the P&A section can seem like cement is the only acceptable plugging material. Although NORSOK states that alternative materials can be used, it will definitely make the interpretations of the requirements more complicated, if an alternative material is chosen, compared to the "standard" cement. For the next revision of NORSOK D-010, it is recommended to generalise the requirements to include alternative plugging materials, and not only specify requirements for cement. To do this, a few adjustments should be made to the document.

6.1 Evaluation of New Alternative Plugging Materials

If adjustments should be made to NORSOK D-010, to implement and optimise for the use of alternative materials, the new materials must be able to document minimum the same level of performance and safety as cement. Comparing the new materials with cement, and evaluating the materials based on compliance with the NORSOK requirements, would address this issue. The comparison is shown in Table 6.1.

Table 6.1: Comparison of Plugging Materials Compliance with NORSOK Requirements

NORSOK Requirements [24]	**Cement**	**Sandaband [19]**	**ThermaSet [30]**
General well barrier requirements			
Positioning	Verified by tagging or logging.	Needs solid foundation to be placed on. Verification by circulation or logging.	Can be tagged or logged to verify position.
Withstand load/pressure	OK	Depending on hydrostatic head, yield point and contact area.	Stronger than cement.
Withstand environmental conditions	Issues relating to temperature cycling and corrosive environments.	Not affected by temperature cycling and corrosion.	Better suited for temperature cycling than cement.
Desired Material Properties for Permanent Barriers			
Impermeable	Permeability depends on the type of cement and the quality of the cement.	Gas tightness verified through tests, dependent on proper composition and hydrostatic head.	Liquid tightness verified through API V3 test. Gas tightness tested [29].
Long-term integrity	Issues relating to temperature cycling and corrosive environments.	Non-degradable particles.	Tested for long-term integrity [23].
Non-shrinking	Initially shrinking during curing, but additives exists to avoid shrinking.	OK	Initially shrinking, regulated by adding of filler or curing under pressure
Ductile	Brittle.	Able to re-shape and conform to the environments through Bingham plastic behaviour.	Significantly more flexible than cement.
Resistance to chemicals (H_2S, CO_2, hydro-carbons)	Corrosive. Mechanical degradation in contact with acid gases.	Non-reactive.	Component with issues removed from design.
Wetting/ bonding capabilities	Could have issues regarding mud-removal and poor hole cleaning.	Similar wetting properties as sand. Does not bond to steel. However, gravity keeps it in place.	5 times cement bonding strength to steel. Same issues regarding mud-removal / hole cleaning.

6.2 General Adjustments

To generalise the requirements and better optimising for alternative materials, one of the most important adjustments would be to define a general term for plugging materials, and switch out the word "cement" with a new term, where general requirements apply. The new term should be a generalised and open term, but at the same time specific enough to accurately explain the material type. The material type relates to the purpose of the material use, which basically is isolation. Therefore, it is recommended to switch out the term "cement" with the more generalised term "isolation material".

When it comes to testing and qualification of the materials, there is a lack of standardisation of test procedures and methods. International standards describe some tests (ISO 10426-2, 10426-3, and 10426-4), but those tests are developed for cement. Industry standards for testing of alternative plugging materials do not exist at this time. However, Oil & Gas UK has started to work on this issue, but the work is not finished yet. They are developing British standards for general testing of all plugging materials, not only for cement. It is recommended that the Norwegian industry develop standards for this type of testing as well. An alternative to developing new standards, could be to evaluate the British standards when they are published, and if they are satisfying, implement these in Norway as well.

6.3 Well Barrier Schematics

WBS are developed as a practical method to demonstrate and illustrate the presence of the defined primary and secondary well barriers in the well. The schematics are very important tools for verification of well barriers and should be compulsory during all well operations, and especially P&A operations. In NORSOK D-010 (Rev. 3, 2004), the creation of WBS is only stated as a recommendation. For the next revision it is recommended to change this expression to a compulsory requirement, for example "Well Barrier Schematics shall be prepared for each well activity and operation."

According to NORSOK D-010 rev. 3, the information on a WBS should include an illustration of the well with the primary and secondary barrier highlighted with colours. It should also include a table with all the WBE that make up the well barrier envelopes, where to find the corresponding WBEACT in Chap. 15 in NORSOK D-010, a space for comments on each WBE, and a field for notes in general.

For the WBS to be even more efficient and useful in P&A operations, it is recommended that the WBS include more information than the example in the last revision of NORSOK D-010.

At the industry-organised (OLF) well-integrity workshop held in March 2007, the need for common, minimum guidelines for the subject WBS was identified to help standardise this tool within the industry. The workshop resulted in calls for establishing a well-integrity forum (WIF) to promote open and frequent discussion of well-integrity related issues amongst the NCS operators. One of the WIF's tasks was to investigate the use of WBS amongst the operating companies and propose a minimum level of detail, which should be included in each well specific WBS. The results are published as a part of the OLF recommended guidelines for well integrity. This is a document supported by the PSA and published by OLF to supplement NORSOK D-010, in areas not adequate covered by NORSOK. The agreed guidelines of minimum data to be included in each well specific WBS are listed below [12], with additional comments/supplements/proposed adjustments:

"1. Reservoir(s) should be shown on the drawing.

The reservoir(s) should be shown on the drawing to be able to verify that the requirements for placement and number of barriers are fulfilled"[12].

Comment: Not only reservoirs, but also other permeable formations / sources of potential inflow/outflow should be shown on the drawing.

"2. Depths should be shown relatively correct according to each barrier element on the drawing.

It is important that the drawing show the barrier elements at the correct depths relative to each other. The relative positioning of the barrier elements is important in relation to integrity, robustness, and the ability to detect any leakages after initial installation and testing. For the same reason, it is also advised to show all packers, PBRs and similar equipment on the drawing. The drawing should be well specific and show/illustrate the actual layout of the well"[12].

"3. All casing and cement, including the surface casing should be on the drawing and labelled with its size.

For the same reason as above, it is important to show all casing sizes and the cement behind. This will give important information of the robustness of the well, and not lead to any misinterpretation of the design"[12].

Comment: Depths of TOC and casing shoe should be indicated for all cement and casing, and other isolation materials should be shown with depths if present. Casing burst/collapse pressure should also be included [22]. This is important because the potential pressure differential shall never exceed the casing burst/collapse pressure, and could influence the positioning of the barriers.

”4. The formation strength should be indicated for formation within the barrier envelopes.

In all well designs, formation will be within the barrier envelopes and may therefore be exposed to reservoir and well pressures. It is important that it is understood which formations are inside the barrier envelopes and ensured that they are not exposed to pressures exceeding their strength. Exceeding the formation strength may result in leaks outside the barrier envelopes. The strength of the formations within the barrier envelopes should therefore be indicated on the barrier drawing and considered when determining operational limits for the well. The formation strength can typically be based on physical measurements performed during drilling of the well, e.g. Formation Integrity Tests (FIT), Leak Off Tests (LOT) or Extended Leak Off Tests (XLOT). The indicated formation strength can also be based on tests done on core samples, results from downhole logs or correlations based on historical field data. The type of value used to indicate formation strength can differ in meaning and uncertainty (e.g. a FIT value has another meaning than a LOT value, a value derived from a downhole log has a higher uncertainty than a value based on tests on core samples), and it should therefore always be stated what the indicated formation strength is based on”[12].

Comment: Formation strength is usually presented in SG units. Without knowing the reservoir pressure and reservoir fluid, the formation strength adds little value to the schematic. However, formation strength data presented as pressure at a true vertical depth (TVD), together with reservoir fluid and pressure data, would improve the value of the WBS [22]. According to NORSOK requirements relating to barrier design load cases, the plug shall not be set shallower than where the worst anticipated reservoir pressure is lower than the formation fracture pressure, to avoid fracturing formation. If set inside a casing string, NORSOK also states that the plug can not be set higher than the casing burst limitations. Therefore, information about the weakest formation strength below plug and casing burst data should be included in the WBS, to be able to control this.

"5. There should be separate fields for the following well information: Installation, well name, well type, well status, and rev. no and date, "Prepared by", "Verified/Approved by".

It is important that the well specific barrier schematic contain information about the validity of the drawing. Therefore installation name and/or field name should be clearly stated, and the name of the well. To be able to understand the well barriers, the "well type"(whether the well is an exploration well, oil producer, water injector, gas injector etc.) should also be stated. The status of the well (whether the well is operational, shut in, temporary or permanently plugged) should also be defined. This is important such that the validity phase of the well barrier schematic is clearly defined. Document and quality control is needed. Revision number, date, information about who has prepared, and who has verified or approved the schematic is therefore also needed"[12].

Comment: In the well information table, for suspended/abandoned wells, the WBS should also include date of suspension/abandonment, reason for suspension/abandonment and expected duration of suspension/abandonment [28]. This could be useful information regarding environment and conditions, and could influence the type of WBE chosen. This could also be useful information when choosing materials for the P&A operation.

"6. Each barrier element in both barrier envelopes should be presented in a table along with its initial integrity-verification test results.

By presenting each barrier element in a table, there will be no doubt regarding which elements are a part of the barrier envelope. In addition, this exercise will help the engineer to ensure the actual elements are qualified according to requirements and the ability to verify the integrity of each element. By stating the actual integrity-verification method and test results for each element on the well barrier schematic, the status of the well is known and documented"[12].

"7. Include a Note field for important well integrity information.

Special well conditions that have changed the barrier envelope over time and other important well integrity information should be highlighted. This ensures any weaknesses are made aware of, and also shows the actual situation. References to where the integrity dispensations are located (e.g. number) should be made, with a short explaining text. The WBS should be updated when well conditions such as e.g. detected tubing/casing leaks, have changed the barrier envelope. Other important well integrity information that has not changed the barrier but still should be highlighted in the note field could e.g. be leaks outside the barrier envelope"[12].

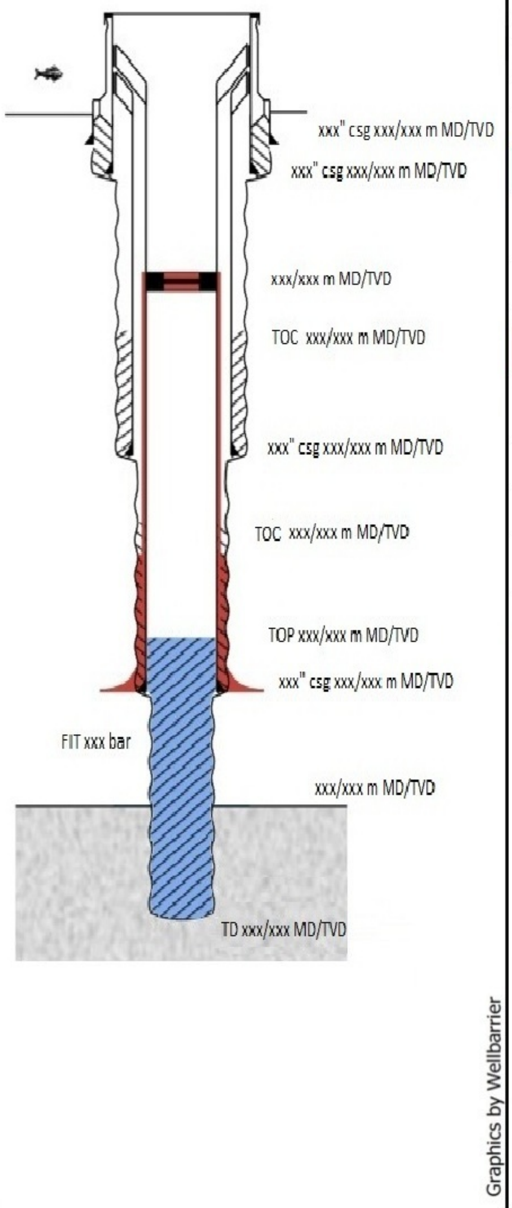
For wells with multiple reservoirs, where a barrier is used as a primary barrier for one reservoir and at the same time as a secondary barrier for another reservoir, these barriers should be coloured with a stapled blue/red colour fill in the drawing. They should also be colour highlighted in the tabular listings. They should be listed one time for each barrier envelope they are a part of, to ensure that there will be no misunderstandings.

To summarise, WBS should contain the following information in addition to the NORSOK rev. 3 requirements:

- The drawing illustrating the well barrier envelopes should show all reservoirs and potential sources of inflow with corresponding depths, pressures, and fluids,
- It should also show all casings, cement, and alternative isolation materials.
- Casing, cement, and alternative isolation materials defined as well barriers elements shall be labelled with its size and depth (TVD and MD),
- The formation strength expressed in pressure unites when the formation is within the well barrier envelope.
- Depth of components should be shown relatively correct in relation to each other.
- Well information should include: Field/Installation, well name, well type, well status, well/section design pressure, date of suspension/abandonment, reason for suspension/abandonment, expected duration of suspension/abandonment, rev. no and date, "Prepared by" and "Verified/Approved by".
- Tables listing the WBE should include columns for qualification and monitoring requirements

Figure 6.1 and Fig. 6.2 shows examples of WBS included for the purpose of illustrating the recommended guidelines mentioned above.

Drawing Ref. :	**Field name** :
Date prepared :	**Well name / no** :
Prepared by :	**Well type** :
Verified by :	**Well status** :
Well design pressure xxx bar	**Reservoir pressure xxx bar**



Temporary abandonment
Cemented open hole, shallow set plug

Reason for abandonment	
Date of abandonment	
Expected duration of abandonment	

Well Activity

Primary Well Barrier

Element	Depth (MD/TVD)	Qualification	Monitoring	Reference to NORSOK WBEACT
Sand slurry plug	From xxx/xxx m to xxx/xxx m	Pressure test to xxx bar		Table 24a

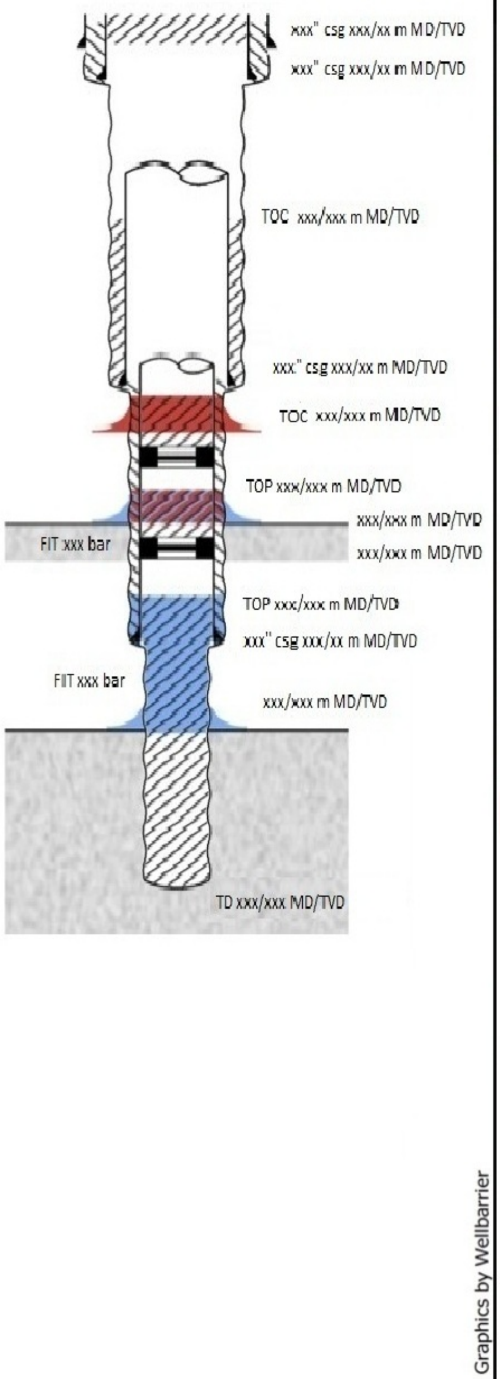
Secondary Well Barrier

Element	Depth (MD/TVD)	Qualification	Monitoring	Reference to NORSOK WBEACT
Mechanical tubular plug	At xxx/xxx m	Pressure test to xxx bar		Table 28
Production casing	From xxx/xxx m to xxx/xxx m	Pressure test to xxx bar		Table 2
Production casing cement	From xxx/xxx m to xxx/xxx m	Job performance, formation integrity test and/or bond log		Table 22

Notes :

Figure 6.1: Example of WBS for temporary P&A of open hole (Illustration by Wellbarrier [28]).

Drawing Ref. :	Field name :
Date prepared :	Well name / no :
Prepared by :	Well type :
Verified by :	Well status :
Well design pressure xxx bar	Reservoir pressure xxx bar



Permanent abandonment
Open hole, formation behind production casing

Reason for abandonment	
Date of abandonment	
Expected duration of abandonment	

Well Activity

Primary Well Barrier, deep reservoir

Element	Depth (MD/TVD)	Qualification	Monitoring	Reference to NORSOK WBEACT
Polymer resin plug set above lower reservoir	From xxx/xxx m to xxx/xxx m	Pressure test to xxx bar	Not available for monitoring	Table 24a
Casing cement at shoe	From xxx/xxx m to xxx/xxx m	Job performance, formation integrity test and/or bond log	Not available for monitoring	Table 22

Secondary Well Barrier, deep reservoir

Element	Depth (MD/TVD)	Qualification	Monitoring	Reference to NORSOK WBEACT
Polymer resin plug set above top reservoir	From xxx/xxx m to xxx/xxx m	Pressure test to xxx bar	Not available for monitoring	Table 24a
Casing cement above top reservoir	From xxx/xxx m to xxx/xxx m	Job performance, formation integrity test and/or bond log	Not available for monitoring	Table 22

Primary Well Barrier, shallow reservoir

Element	Depth (MD/TVD)	Qualification	Monitoring	Reference to NORSOK WBEACT
Polymer resin plug set above top reservoir	From xxx/xxx m to xxx/xxx m	Pressure test to xxx bar	Not available for monitoring	Table 24a
Casing cement above top reservoir	From xxx/xxx m to xxx/xxx m	Job performance, formation integrity test and/or bond log	Not available for monitoring	Table 22

Secondary Well Barrier, shallow reservoir

Element	Depth (MD/TVD)	Qualification	Monitoring	Reference to NORSOK WBEACT
Cement plug set at interval higher up in the production casing	From xxx/xxx m to xxx/xxx m	Pressure test to xxx bar	Not available for monitoring	Table 24
Casing cement at interval higher up in the production casing	From xxx/xxx m to xxx/xxx m	Job performance, formation integrity test and/or bond log	Not available for monitoring	Table 22

Notes:

Figure 6.2: Example of WBS for permanent P&A of multiple reservoirs with a common well barrier (Illustration by Wellbarrier [28]).

6.4 Well Barrier Acceptance Criteria

Regarding WBEAC, there are also a few aspects that should be discussed when using alternative plugging materials instead of cement. Based on cement, NORSOK requires two independent well barriers, in addition to specific minimum length requirements for the cement plug. These requirements might not be optimal for alternative materials.

Length of plug

The length requirements are based on cement, and NORSOK states that a cement plug shall have a minimum length of 100m MD. Around the world, different length requirements exists, for example

- Canada requires 15 m (50 ft) [4]
- UK, Australia & Mexico requires 30 m (100ft) [11]
- USA used to require 30 m (100 ft), but increased to 60 m (200 ft) after the Macondo incident [6]
- Russia requires 68,5 m (225 ft)
- Norway, Netherlands & Germany requires 100 m (330 ft) [8]

As we can see, the requirements are varying a lot, and it seems like there is no common understanding of the amount of cement that should be required. The reason is that the number in the requirements is just a safety margin to ensure that there will be enough cement of satisfying quality for the plug to meet the functional barrier requirements. The permeability of cement varies with the quality of the cement. Good cement provides extremely low permeability, while poor cement could have high permeability, and potential fractures and microannuli. You never know how the quality of the cement plug varies down the hole, because the only verification methods are volume calculations, tagging of TOC, and pressure testing the plug as a whole. These verification methods do not show how the cement plug quality varies. If it was possible to verify cement more accurately, the length requirements would probably be less, and the quality requirements would be more specified and stricter.

For other materials like Sandaband and ThermaSet, the general impression is that these alternative materials do not have the same amount of problems as cement. Sandaband, with no curing time, avoids all the issues with curing, and could therefore be assumed to have less variation in quality along the hole, meaning less need for a large safety margin length. On the other hand, Sandaband improves its strength when the hydrostatic head increases, so a longer plug would mean a stronger and better plug. It is important to note, however, that the length requirements of 100 m MD for cement would have less influence on a Sandaband plug, since it is the TVD that influences the hydrostatic head and therefore the biggest contribution for the strength of the Sandaband plug. The length of the plug also has some issues for Sandaband in combination with positioning of the plug. NORSOK requires the plug to be placed as close to the potential source of inflow as possible. For a cement plug, among the additional length requirements, there exist a requirement that the plug shall extend 50 m MD above the source of inflow. This means, to minimum meet the required 100 m MD plug length, that the plug can be set from 50 m MD below the highest point of inflow to 50 m MD above. For Sandaband, which strength is mainly based on the hydrostatic head of the column, these length and positioning requirements could be inadequate. The Sandaband plug should be designed to meet the requirements of the highest point of potential inflow, and the length requirements should therefore apply from this point and upwards only. For Sandaband, the requirements should be expressed in TVD, or specific design requirements based on yield-point and cross sectional contact area in deviated/horizontal wells should be developed.

As a uniform resin, ThermaSet could also be expected to have less variations in quality, compared to the complex cement slurry mix. ThermaSet is also stronger than cement, and could perhaps provide the same level of safety as cement with a shorter plug length. But again, a longer plug would in general mean a better plug, so why change the requirements to the less? Well, there is no need to “overkill” the strength of the plug either. If a shorter plug of an alternative material would provide sufficient strength and safety, there is no need for a longer plug. The most obvious reason to change the plug length requirements to the less would be to save time and money. Some plugging operations include milling and cutting of casing, which are time consuming and costly operations. A shorter required milling/cutting interval could potentially mean enormous cost reduction.

Number of Barriers

Sandaband also needs a solid foundation to be placed on. This makes Sandaband dependent on assistance of some other plug/material to fulfil the requirements of two barriers including length requirements. In the governing Oil & Gas UK Guidelines for the Suspension and Abandonment of wells, the regulations opens for the possibility to "combine two independent well barriers into a single large permanent barrier, provided it is as effective and reliable as the two barriers and is an appropriate method to achieve the objectives that two barriers would otherwise have proved" [11]. When a combination barrier is chosen, it should also be fully risk-assessed and documented. For Sandaband, a combination barrier might be a better solution in some cases, because the hydrostatic head would increase and make the plug withstand higher pressures, but also the need for a solid foundation to be placed on would be reduced. Only one plug requires only one foundation and this could be the bottom of the well in some cases. To be able to remove the need for a mechanical plug improves the verification methods as well, since a pressure test would actually be testing the Sandaband plug, instead of the mechanical plug (which should not be regarded as a permanent barrier in the first place according to NORSOK). The increasing hydrostatic head caused by a combination plug would increase the strength of the plug, but it could also, if exceeding the formation strength, lead to fracturing of the formation. Apart from potentially creating leak paths outside the barrier envelope, this should, however, not lead to any major issues, because of Sandabands ability to plug the fractures and experience almost zero losses.

For cement, a combination barrier would have both advantages and disadvantages. The increased length would increase the probability of obtaining a sufficient length of good quality cement, for example by better hole cleaning to avoid contamination of the cement slurry. Disadvantages include higher probability of experiencing losses and problems with cementing inside stinger when pulling out slowly during placement of a balanced plug.

In general we can assume that a longer plug would mean a better plug, but the fact that a well plugged and abandoned with a combination barrier solution relies only on one barrier, is the most concerning one. The main purpose of the two independent barriers requirement is that the well should maintain its integrity and remain sealed even though one barrier fails. At the same time it is important to minimize the potential of a barrier failure, it is also important to minimize the consequences of a barrier failure. If a combination barrier fails, there is no back-up barrier to minimize the consequences. Reasons of failure and changing conditions downhole are hard to predict, and this is why NORSOK, with its requirement for two independent barriers, takes a possible single barrier failure into account, and requires a backup. Just in case. This requirement of two independent barriers applies to all operations at all times and is also regarded as one of the main principles throughout the whole NORSOK D-010 standard. It should also be mentioned that the last US regulation revision, after the Macondo incident, now requires two independent barriers, opposed to only one before [6].

6.5 Well Barrier Element Acceptance Criteria Tables

Although the latest revision of NORSOK D-010 does not specify cement alternatives individually, it does open for the use of alternative materials as long as these go through a qualification process, and an overview of relevant well barrier element acceptance criteria (WBEAC) is made. Chapter 15 of the standard includes 50 different WBEACT, but the only plugging material covered is cement. As long as the cement requirements are clearly stated in WBEACT, while the alternative materials corresponding requirements are lacking, cement would be easier to prefer as the material for the operation, even though an alternative material could have improved the quality of the WBE. It is recommended to either generalize the cement WBEACT to cover all plugging materials, or to include specific WBEACT for alternative plugging materials in the next revision of the standard.

To generalize the cement requirements to cover all alternative materials would make the new requirements less specific. This could make the requirements less useful, because one of the most important goals for the acceptance criteria tables are to have specific requirements easy to relate to. It could also be difficult to generalize the cement requirements because of large differences in material properties compared to some alternative materials, so it would perhaps be a better solution for well-known, tested and qualified alternative materials, such as Sandaband and ThermaSet, to develop and include new specific WBEACT. During the last few years, Sandaband Well Plugging AS has performed various tests in cooperation with the industry and research institutions to qualify Sandaband as a gas tight plugging material. In the evaluation of Sandaband compliance to NORSOK requirements, performed by Proffshore, two proposals for WBEACT for Sandaband (Appendix A and B) was developed [16]. The intention was for the WBEACT to be implemented in NORSOK D-010, but since the WBEACT was made in 2005, after the last revision of NORSOK in 2004, it was not included. Because Sandaband has been more accepted and used in the industry since the last revision of the NORSOK standards, it is recommended to include the WBEACT in the upcoming revision. However, the tables made by Proffshore should also be revised, since it is 7 years since they were developed, and Sandaband has developed and gained more experience since that. A recommended improvement would be to include a specific requirement for the plug length safety margin, and that this length should be given in TVD. Alternatively/additionally, a specific requirement regarding yield-point and contact area should be developed.

There should also be developed two WBEACT for ThermaSet to make it easier to qualify ThermaSet as a WBE, as fill behind casing and as a plug, in the same way as Proffshore did for Sandaband. Suggestions for WBEACT for ThermaSet are proposed and shown in Table 6.2 and Table 6.3. As most of the properties as a plugging materials is similar to cement, the tables are based on the corresponding tables for cement. However, some of the requirements have been adjusted and/or added. Some of the remaining requirements could perhaps also be adjusted, if more information regarding testing, qualification and verification existed. The most important difference is that the placement and curing time of ThermaSet is controlled by temperature, and should therefore be particularly addressed as a very important requirement to fulfil. Other requirements that could be modified would be the plug length, and verification methods. As these subjects have not been satisfactory tested and qualified, the length requirements and pressure testing requirements are assumed to be the same as for cement. The general material name of a “polymer resin“ sealant is chosen, in order to open up for similar alternative materials as ThermaSet, just as the name “sand slurry“ is used for the Sandaband tables.

Table 6.2: Suggestion for WBEACT for Polymer Resin Plug

<table>
<tr><th>Features</th><th>Acceptance Criteria</th><th>References</th></tr>
<tr><td>A. Description</td><td>The element consists of a polymer resin sealant in solid state that forms a plug in the wellbore.</td><td></td></tr>
<tr><td>B. Function</td><td>The purpose of the plug is to prevent flow of formation fluids inside a wellbore between formation zones and/or to surface/seabed.</td><td></td></tr>
<tr><td>C. Design, construction and selection</td><td>1. A design and installation specification (pumping program) shall be issued for each resin plug installation.
2. The properties of the set polymer resin plug shall be capable to provide lasting zonal isolation. Permanent polymer resin plugs should be designed to provide a lasting seal with the expected static and dynamic conditions and loads down hole. It shall be designed for the highest differential pressure and highest downhole temperature expected, inclusive installation and test loads.
3. The polymer resin shall be designed to cure at the representing temperatures at placement.
4. The firm plug length shall be 100 m MD. If a plug is set inside casing and with a mechanical plug as a foundation, the minimum length shall be 50 m MD.
5. It shall extend minimum 50 m MD above any source of inflow/leakage point. A plug in transition from open hole to casing should extend at least 50 m MD below casing shoe.
6. A casing/liner with shoe installed in permeable formations should have a 25 m MD shoe track plug.</td><td></td></tr>
<tr><td>D. Initial test and verification</td><td>1. Cased hole plugs should be tested either in the direction of flow or from above.
2. The strength development of the polymer resin should be verified through observation of representative surface samples from the mixing cured under a representative temperature and pressure.
3. The plug installation shall be verified through documentation of job performance; records fm. pumping operation (volumes pumped, returns during pumping, etc.).
4. Its position shall be verified, by means of:
This describes the methods for verifying that the WBE is ready for use after installation in/on the well and before it can be put into use or is accepted as part of well barrier system.
<table>
<tr><th>Plug type</th><th>Verification</th></tr>
<tr><td>Open hole</td><td>Tagging, or measure to confirm depth of firm plug</td></tr>
<tr><td>Cased hole</td><td>Tagging, or measure to confirm depth of firm plug Pressure test, which shall
1. be 7000 kPa (~1000 psi) above estimated formation strength below casing / potential leak path, or 3500 kPa (~500 psi) for surface casing plugs, and
2. not exceed casing pressure test, less casing wear factor which ever is lower.
If a mechanical plug is used as a foundation for the resin plug and this is tagged and pressure tested the resin plug does not have to be verified.</td></tr>
</table></td><td></td></tr>
<tr><td>E. Use</td><td>Ageing test may be required to document long-term integrity</td><td></td></tr>
<tr><td>F. Monitoring</td><td>For temporary suspended wells: The fluid level / pressure above the shallowest set plug shall be monitored regularly when access to the bore exists.</td><td></td></tr>
<tr><td>G. Failure modes</td><td>Non-compliance with above mentioned requirements and the following:
1. Loss or gain in fluid column above plug.
2. Pressure build-up in a conduit, which should be protected by the plug.</td><td></td></tr>
</table>

Table 6.3: Suggestion for WBEACT for Polymer Resin as Barrier Behind Casing

Features	Acceptance Criteria	References
A. Description	This element consists of polymer resin sealant in solid state positioned in the annulus between concentric casing strings, or the casing/liner and the formation.	
B. Function	The purpose of the element is to provide a continuous, permanent and impermeable hydraulic seal along hole in the casing annulus or between casing strings, to prevent flow of formation fluids, resist pressures from above or below.	
C. Design, construction and selection	1. A design and installation specification (pumping program) shall be issued for each pumping job. 2. The properties of the set polymer resin shall be capable to provide lasting zonal isolation. 3. Polymer resins used for isolating permeable and abnormally pressured hydrocarbon bearing zones should be designed to prevent gas migration. 4. The resin placement technique applied should ensure a job that meets requirements whilst at the same time imposing minimum overbalance on weak formations. ECD and the risk of lost returns during pumping shall be assessed and mitigated. 5. The polymer resin shall be designed to cure under representative temperatures at placement. 6. Height requirements: The height of the polymer resin column shall be minimum 100 m MD. 7. Temperature exposure, cyclic or development over time, shall not lead to reduction in strength or isolation capability. 8. Requirements to achieve the along hole pressure integrity in slant wells to be identified.	
D. Initial test and verification	1. The polymer resin shall be verified through formation strength test when the casing shoe is drilled out. Alternatively the verification may be through exposing the resin column for differential pressure from fluid column above resin in annulus. In the latter case the pressure integrity acceptance criteria and verification requirements shall be defined. 2. The verification requirements for having obtained the minimum polymer resin height shall be described, which can be • verification by logs (gravel pack evaluation, bond log), and/or • estimation on the basis of records from the pumping operation (volumes pumped, returns during pumping, etc.). 3. The strength development of the polymer resin shall be verified through observation of representative surface samples from the mixing cured under a representative temperature and pressure. For HPHT wells such equipment should be used on the rig site.	
E. Use	Ageing test may be required to document long-term integrity	
F. Monitoring	1. The annuli pressure above the polymer resin well barrier shall be monitored regularly when access to this annulus exists. 2. Surface casing by conductor annulus outlet to be visually observed regularly.	
G. Failure modes	Non-fulfilment of the above requirements (shall) and the following: 1. Pressure build-up in annulus as a result of e.g. micro-annulus, channelling in the resin column, insufficient volumes placed in the well, excessive contamination of the material during placement etc.	

6.6 Evaluation of the Proposed Changes

Being based on cement, the current revision of the NORSOK D-010 requirements do not encourage the use of alternative plugging materials. With all the known problems and challenges of cement; this is one of the greater weaknesses of the standards regarding P&A operations. The industry always searches for better solutions, and in general, preparation and optimisation for new technology would be advantageous, to keep up with the latest industry developments. On the other hand, such new developments should also always be addressed with caution, to ensure the quality of the new technology. New technologies have limited field experience, so it is important to be able to document testing and qualification properly, to ensure that the performance undoubtedly will be satisfying. With new P&A materials, it is especially important to document the long-term integrity, because the material is new and has insufficient long-term experience. It is hard to convince the industry to use new materials with limited field experience, especially when the standards requires so much extra effort if new materials is chosen. To be able to encourage new developments, the standards should be revised frequently with focus on new technological developments.

Changing "cement" to "isolation material"

The most important change in the next revision of NORSOK D-010 would therefore be to switch out the word "cement" with another more generalised term. This would really open up for the use of new alternative materials. It is recommended to use the term "isolation material" instead of "cement". This means that the standard no longer regard cement as the only isolation material. Generally, this is a great improvement. Cement would still be regarded as an isolation material, so the requirements for cement would not change. In challenging conditions for cement, this change would obviously be an advantage, allowing better-suited materials to be used to replace cement. It could be beneficial both regarding safety, but also in the economical aspect, resulting from the potential of reducing the need for repair operations if the cement should fail in the challenging conditions. However, it is important to notice that the alternative materials have to meet certain requirements ensuring at least the same level of safety as cement.

Length of Plug

Changing the requirements for plug length is a difficult theme, because there seems to be no common understanding in the industry of what the exact plug length needs to be. On a world basis, NORSOK is in the stricter end with its plug length requirement of minimum 100 m MD. Introducing new materials with different properties means that the length requirements could be adjusted. For Sandaband, the required length should depend on the design of the specific well, because the length of the plug provides the hydrostatic head, which is critical for the strength of the plug. In this case, the length should depend on the expected differential pressure the plug is required to withstand. For ThermaSet, the length requirements could perhaps be less than for cement, as discussed in Sec. 6.4. A general change in the length requirement is not possible, because of the varying material properties. In this case it is recommended to implement different length requirements in the new specific material WBE acceptance criteria, while the cement length requirements are recommended to remain unchanged. In this way, the safety level is kept at the same level as before.

Combining Two Independent Barriers Into One Large Permanent Barrier

Even though the UK opens for the combination barrier solution, it requires the combination barrier to ensure the same level of safety as the two independent barriers. This is of course hard to document. With the introduction of new materials, the combination barrier could be a good solution, but even though the barrier would improve its strength, there is always some chance of a barrier failure. The principle of two independent barriers is one of the main principles in NORSOK D-010, and it is recommended to keep this requirement unchanged.

Well Barrier Schematics

WBS are very important tools for verification of well barriers, and it is recommended to make the development of WBS a requirement instead of just a recommendation. This would improve the general safety by ensuring the existence of such WBS, providing an overview of the well barriers and increasing the probability of detecting potential leak paths and/or design problems. It is a common impression in the industry that the WBS in the last revision of NORSOK D-010 does not include enough information. More information would make the WBS more efficient and give a better view of the barrier situation.

Well Barrier Element Acceptance Criteria

Because there are no other specific requirements than those for cement, it is recommended to include 4 new WBEACT to implement the new alternative materials in the standard. This would make it easier to use the new materials because one would have specific acceptance criteria to fulfil. If the developed acceptance criteria ensure a high enough level of safety and quality, these additions would improve safety, by optimizing for, and encouraging the use of new materials better suited for some conditions. It is therefore extremely important that these tables impose requirements that ensure sufficient quality regarding HSE.

7 Conclusion

One of the main improvements in P&A technology since 2004 is the development of new alternative plugging materials to cement. The main problem when preparing the new materials for use, is the lack of standards for testing & qualification of alternative materials for P&A operations. Such standards should be developed, in addition to adjusting and optimizing the requirements in NORSOK D-010, to ensure the quality of new alternative materials in the future. After evaluating the current requirements against the new materials Sandaband and ThermaSet, it is recommended to implement the following changes to NORSOK D-010:

- Change the word "cement" in general sections to "isolation material"
- Make specific plug length requirements for alternative isolation materials
- Make the development of WBS a compulsory requirement
- Extend the required information in the WBS to include the following information:
  - The drawing illustrating the well barrier envelopes should show all reservoirs and potential sources of inflow with corresponding depths, pressures, and fluids,
  - The drawing should also show all casings, cement, and alternative isolation materials.
  - Casing, cement, and alternative isolation materials defined as well barriers elements shall be labeled with its size and depth (TVD and MD),
  - The formation strength expressed in pressure unites when the formation is within the well barrier envelope.
  - Depth of components should be shown relatively correct in relation to each other.
  - Well information should include: Field/Installation, well name, well type, well status, well/section design pressure, date of suspension/abandonment, reason for suspension/abandonment, expected duration of suspension/abandonment, rev. no and date, "Prepared by" and "Verified/Approved by".
  - Tables listing the WBE should include columns for qualification and monitoring requirements

- Include 4 new WBEACT:
  - Sand slurry plug
  - Sand slurry as a barrier behind casing
  - Polymer resin plug
  - Polymer resin sealant as barrier behind casing

All the proposed changes above will improve the implementation of alternative plugging materials. They are also expected to improve the overall safety of P&A operations. None of the proposed changes is expected to lower the level of safety.

In addition to implementing these adjustments and changes to the NORSOK D-010, it is strongly advised to revise the document more frequently than every 8 years, as the situation is now. A revision every 2-3 years would improve the standards, and ensure that new developments and experiences are continuously implemented.

8 Recommendations for Further Work

- Revise NORSOK D-010. This work has already been announced and is expected to be finished late 2012
- Either develop Norwegian standards for testing and qualification of alternative plugging materials, or implement the UK requirements, which are being developed at this time.
- Perform more testing on new materials, especially long term integrity testing.
- More research on what should be the required minimum length of a plug, both with cement and other materials.

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Appendices

Appendix A

Table A.1: WBEACT for Sand Slurry as Barrier Behind Casing [16]

Features	Acceptance Criteria	References
A. Description	This element consists of impermeable sand slurry material in solid state with Bingham plastic behaviour located in the annulus between concentric casing strings, or the casing/liner and the formation.	
B. Function	The purpose of the element is to provide a continuous, permanent, flexible and impermeable hydraulic seal along hole in the casing annulus or between casing strings, to prevent flow of formation fluids and resist pressures from above or below. It will reshape to changes in geometry from e.g. faults, subsidence and temperature etc.	
C. Design, construction and selection	1. A design and installation specification (pumping program) shall be issued for each pumping job. 2. The material shall be capable to provide lasting zonal isolation. 3. The plug shall be prevented from longitudinal movement by either 1. having sufficient height and length such that its combined weight and yield point overcome initial (non-depleted) reservoir pressure; or: 2. being anchored with a permanent solid material on the top and bottom. 3. The material shall not be placed on top of a fluid column allowing gravitational settling. 4. Temperature exposure, cyclic or development over time, shall not lead to reduction in strength or isolation capability.	
D. Initial test and verification	• The combined element consisting of material and foundation shall be verified through formation strength test when the casing shoe is drilled out. Alternatively, the verification may be performed through exposing the column for differential pressure from fluid column above the material in the annulus. In the latter case the pressure acceptance criteria and verification requirements shall be defined. • The verification requirements for having obtained the minimum height shall be described, which can be 1. verifications by logs (gravel pack evaluation, bond log), and/or 2. estimation on the basis of records from the pumping operation (volumes pumped, returns during pumping, etc.). • Properties of each batch of material produced shall be verified by laboratory testing to be within accepted values for density and water content to ensure sealing capability. This shall be documented in the batch certificate issued by the manufacturing plant.	
E. Use	None	
F. Monitoring	1. The annuli pressure above the well barrier shall be monitored regularly when access to this annulus exists. 2. Surface casing by conductor annulus outlet to be visually observed regularly.	WBEAC for "wellhead"
G. Failure modes	Non-fulfilment of the above requirements (shall) and the following: 1. Pressure build-up in annulus as a result of e.g. insufficient volumes placed in the well, excessive contamination of the material during placement, etc.	

Appendix B

Table B.1: WBEACT for Sand Slurry Plug [16]

<table>
<tr><th>Features</th><th>Acceptance Criteria</th><th>References</th></tr>
<tr><td>A. Description</td><td>The element consists of Sand slurry material in solid state with Bingham plastic behaviour that forms a plug in the wellbore.</td><td></td></tr>
<tr><td>B. Function</td><td>The purpose of the plug is to prevent flow of formation fluids inside a wellbore between formation zones and/or to surface/seabed.</td><td></td></tr>
<tr><td>C. Design, construction and selection</td><td>1. A design and installation specification (pumping program) shall be issued for each plug installation.
2. The in-situ plug shall remain deformable and conform (i.e. remain homogenous) to the cross sectional area in the wellbore and be capable to provide everlasting zonal isolation.
3. Plug shall not fracture with exposure to temperature and pressure cycling or mechanical loading.
4. The plug length shall be designed for the highest differential pressure and highest downhole temperature expected at any point in time, inclusive installation and test loads.
5. The full volume for the plugging job shall be defined for the plug in order that a homogenous slurry can be made in a controlled onshore facility and be shipped to the wellsite avoiding any contamination on surface, downhole and whilst spotting downhole.
6. The plug shall be placed on a verified (load and pressure tested) mechanical foundation or on the bottom of the wellbore to ensure gravitational support.</td><td></td></tr>
<tr><td>D. Initial test and verification</td><td>1. Cased hole plugs should be tested either in the direction of flow or from above.
2. Properties of each batch of material produced shall be verified by laboratory testing to be within accepted values for density and water content to ensure sealing capability. This shall be documented in batch certificate issued by the manufacturing plant.
3. The plug installation shall be verified through documentation of job performance; records fm. pumping operation (volumes pumped, returns during pumping, etc.).
4. Its position should be verified, by means of:
<table>
<tr><th>Plug type</th><th>Verification</th></tr>
<tr><td>Open hole</td><td>Dressing off at top of the plug and verifying returns at surface</td></tr>
<tr><td>Cased hole</td><td>Dressing off at top of the plug and verifying returns at surface
Pressure test, which shall:
1. Be 7000 kPa (~1000 psi) above estimated formation strength below casing/ potential leak path, or 3500 kPa (~500 psi) for surface casing plugs, and
2. not exceed casing pressure test, less casing wear factor which ever is lower</td></tr>
</table></td><td></td></tr>
<tr><td>E. Use</td><td>Ageing test is not required to document long-term integrity. Sand slurry material consists of non-degradable quartz and water.</td><td></td></tr>
<tr><td>F. Monitoring</td><td>For temporarily suspended wells: The fluid level/pressure above the shallowest set plug shall be monitored regularly when access to the bore exists.</td><td></td></tr>
<tr><td>G. Failure modes</td><td>Non-compliance with above mentioned requirements (shall) and the following:
1. Loss or gain in fluid column above plug.
2. Pressure build-up in a conduit, which should be protected by the plug</td><td></td></tr>
</table>

Appendix C

NORCEM
HEIDELBERGCEMENT Group

TEST CERTIFICATE

NORWELL, API Class G, Well Cement

HIGH SULFATE RESISTANT (HSR)

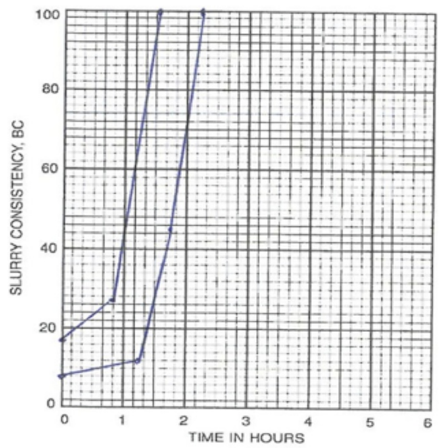
TESTED IN ACCORDANCE WITH API SPEC 10A / NS-EN ISO 10426-1

Delivery No.: FD8-12

1205 tons Cement Class G, shipped from our works by mbc CORK bound for Mongstad and Florø April 19th 2012.

PHYSICAL TESTS :	Results :	Requirements :
Fineness, Blaine	336 m^2/kg	
Free Fluid	2.1 %	5.9 % Max.
COMPRESSIVE STRENGTH :		
8-Hour Curing Time:		
38°C, Atmos. Pressure :	1192 psi	300 psi Min.
60°C, Atmos. Pressure :	2762 psi	1500 psi Min.
THICKENING TIME TEST :		
Schedule No. 5:		
Max. Consistency 15-30 Minute Stirring Per. :	19 Bc	30 Bc Max.
Thickening Time (100 Bc) :	93 Minutes	90-120 Minutes
CHEMICAL COMPOSITION :		
Cr^{6+}	0.00 mg/kg	
MgO	1.69 %	6.0 % Max.
SO_3	2.11 %	3.0 % Max.
L.O.I.	0.71 %	3.0 % Max.
Insoluble Residue	0.33 %	0.75 % Max.
3 CaO*SiO_2	58.7 %	65.0 % Max.
		48.0 % Min.
3 CaO*Al_2O_3	1.3 %	3.0 % Max.
4 CaO*Al_2O_3*Fe_2O_3+ 2*(3 CaO*Al_2O_3)	18.7 %	24.0 % Max.
Na_2O Eq.	0.67 %	0.75 % Max.

Schd. 5 Schd. 7g



Brevik, April 19th 2012

Laboratory Manager

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Figure C.1: Norcem test certificate Norwell - API spec 10A / NS-EN ISO 10426-1 [9]

NORCEM
HEIDELBERGCEMENT Group

NORWELL, API Class G, Well Cement

ADDITIONAL TESTS

DELIVERY No.: FD8-12

SLURRY DENSITY :

44 percent Water By Weight of Cement	16.10 lb/gal

RHEOLOGICAL PROPERTIES :

Viscometer Dial Reading at 300 rpm	106
Viscometer Dial Reading at 200 rpm	92
Viscometer Dial Reading at 100 rpm	76
Viscometer Dial Reading at 60 rpm	68
Viscometer Dial Reading at 20 rpm	55
Viscometer Dial Reading at 6 rpm	31
Viscometer Dial Reading at 3 rpm	23
Plastic Viscosity (PV) = 1,5*(A-B)	45 cP
Yield Point (A-PV)	61 lbf/100 ft2
10-Minute Gel Strength, 3 rpm, max.	36 lbf/100 ft2
- After 30 sec. stirring	17 lbf/100 ft2
- After 1 min. stirring	15 lbf/100 ft2
- After 2 min. stirring	17 lbf/100 ft2

RETARDER RESPONSE :

Schedule No. 7g 185°F with 0,4% R6-AB

Max. Consistency 15-30 Minutes Stirring Period	8 Bc
Thickening Time, 100 Bc	135 Minutes

Brevik, April 19th 2012

kcs.
KCS.

Laboratory Manager

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Figure C.2: Norcem test certificate Norwell - additional tests [9]