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List of Abbreviations

§	Paragraph
ALARP	As low as reasonably practicable
API	American Petroleum Institute
BSSE	Bureau of Safety and Environmental Enforcement
CO2	Carbon dioxide
EAC	Element acceptance criteria (Well barrier)
FCP	Fracture closure pressure
FIT	Formation integrity test
H2S	Hydrogen Sulphide
ISO	International standard Organisation
LOT	Leak-off test
M	Meter
MD	Measured depth
NCS	Norwegian Continental Shelf
NOGA	Norwegian Oil and Gas Association
NOK	Norwegian Kroners
NPD	Norwegian Petroleum Directorate
NTL	Notice to Lessees
P&A	Plug & Abandonment
PIT	Pressure integrity test
PSA	Norwegian Petroleum Safety Authorities
PWC	Perforated wash cement
Rev	Revision
WBE	Well barrier element
XLOT	Extended leak-off test

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Summary

This master thesis presents the development of the regulation in the field of permanent plug and abandonment in the Norwegian Continental Shelf (NCS). It describes how the regulations have been developed for Permanent Plug and Abandonment (P&A) and focusing on effects of regulations since 1967.

The overall aim of the work is to highlight major changes in the regulations and assess the effects on the oil and gas industry in Norway. In addition, I am focusing on the barriers and barrier management in P&A operations and how the operating companies in Norway implemented and complied with the requirements.

The first chapter of the thesis is a general introduction to regulations and standards related to the P&A in the NCS. The second chapter describes the development of the regulations and describes the main actors in developing these requirements. While the third chapter describes the historical developments in details from the first issued regulation to the establishment of the NORSOK standard D-010 with specific focus on drilling activities and well activities.

The fourth chapter describes the major changes in NORSOK D-010 and describing the major changes in details.

The fifth chapter is focusing on the barriers, well barriers and well barrier acceptance criteria, and defines how the Norwegian management regulation section 5 is emphasizing that the barriers shall be established at all times. The sixth chapter of the thesis is highlighting the data selection process and present the scope of P&A activities by fields and major operating companies in NCS.

The analysis part in chapter seven is focusing on the effects of the changes in regulation on issues related to; integrity, HSE, costs, effectiveness, resource utilisation and the need for the technology development in the field of P&A.

The eighth chapter is the discussion part where I have interpreted and described the significance of the findings and the effects on the operations in the field of P&A: The chapter is explaining the developments in the regulation, challenges and main actors in the field. The primary source of data, information on wells and well status discussed with the currently available knowledge in the field.

This thesis provides the overview of the changes in regulations, the need for more in-depth research in the field in the future. As it is presented in chapter nine for conclusions, the presenting findings are based on my experience with gathered data, communications with major oil and gas operating companies and with Norwegian Petroleum Safety Authorities. The finding from the thesis is clearly indicating the possibility for improvements in data quality, feedback from industry to students and researchers as well as evaluating the need for establishing a monitoring system for all permanently plugged wells.

1. Introduction

This study is covering the area of the historical development of the regulations and standards related to the permanent plug and abandonment (P&A) in the Norwegian continental shelf.

The thesis addresses the development of the regulations related to permanently plugging and abandonment of wells in the Norwegian Continental shelf and how these developments have affected the P&A design, operations, safety and other issues related to cost, technology development and effectiveness of operations.

The thesis will focus on the main characteristics of the P&A and the issues related to the barrier management in permanently plugged wells, as well as main changes on the regulations and the development of the main Standards in Norway.

The theoretical basis for this study is based on several methods of collecting data and information which mainly based on: -

- Review the regulations and standards related to P&A
- Review the literature on the P&A
- Contact the major operators
- Collect data on all P&A wells from 1967 to 2017
- Analyse the data
- Define the status of the wells
- Evaluate the effect of the regulations changes on the status of the wells

In the last years, the development and the adaption of the NORSOK Standards as the main standard in oil and gas industry for P&A and its implementation by major oil and gas companies have led to a deep focus and adherence of the companies to all the elements in the standard.

This thesis is focusing on the main characteristics of Norway and the Norwegian continental shelf. The Norwegian regulatory system is based on “the principle that anyone who conducts or participates in petroleum activities shall comply with legal provisions, including regulatory decisions which are made pursuant to the Petroleum Act. More specifically, this duty requires such parties to actively seek to bring identified discrepancies into compliance” (NPD, 2012).

The Petroleum Act (Act No. 72 of 29 November 1996 relating to petroleum activities) provides the general legal basis for the licensing system that governs Norwegian petroleum activities. It covers all phases of the petroleum activities, from the application of licences, awarding, exploration, construction, production and the plans for field cessation including the plugging and abandonment of the wells.

“As a main rule, the Petroleum Act requires licensees to submit a cessation plan to the Ministry, two to five years before the licence expires, is relinquished or before the use of a facility ceases. The cessation plan must have two main sections; an impact assessment section and a disposal section. The impact assessment provides an overview of the expected consequences of the disposal for the environment and other factors. The disposal section must include proposals for how the cessation of petroleum activities on a field can be accomplished” (NPD, 2014).

In Norway, the Norwegian Parliament has the responsibility in setting the framework for the petroleum activities in the country and its territories. “In addition to the adaptation of the legislations, the parliament also reviews the Government and all public administration institutions” (NPD, 2014). To carry out the legislation and assuring the appropriate implementation of the legislations and regulations, “the Government is assisted by the ministries, underlying directorates and supervisory authorities” (NPD, 2014).

These responsibilities are divided among various ministries according to their role in adapting the Norwegian petroleum policy. The ministries are as follows:

- The ministry of petroleum and energy
- The ministry of labour and social affairs
- The ministry of finance
- The ministry of transport and communications
- The ministry of climate and environment.

The Norwegian petroleum directorate is a subordinate to the ministry of petroleum and energy. The Petroleum Safety Authority (PSA) is subordinate to the ministry of labour and social affairs.

The major legal frameworks for petroleum activities in Norway are:

- Act relating to petroleum activities (29th November 1996, last amended 24.6.2011)
- Regulations to Act relating to petroleum activities (Royal Decree 27 June 1997, last amended in 2.7.2012)

The major regulatory issues: (NPD, 2012)

- Management system requirements
- Requirements concerning the organising, planning and implementation of the activities
- Technical requirements for the design and operating of the metering equipment
- Metering equipment and measurement methods required to provide adequate accuracy and reliability at all times.

In the debate at the Norwegian Parliament House (11 November 2015), the Minister of oil and energy has stated that: in Norway, “we have good health, safety and environment framework on the Norwegian shelf” (Lien, 2015). He considered that “there is a broad consensus regarding this. When it comes to well integrity, there are also regulations that have been tightened in recent years”. He emphasized on the “Norwegian authorities are concerned that health, safety and environment - also the external environment - are handled in a right way with current laws and regulations” (Lien, 2015).

The Regulations in Norway started in 1967 with general regulations related to geological operations on NCS and it has been followed by some specific regulations covering the management of oil and gas activities in Norway.

- First regulations 1967: Royal decree of 25th August 1967 relating to Safe Practice, etc. in the Exploration and Drilling for Submarine Petroleum Resources
- Second regulations 1975: Regulations for drilling for petroleum in Norwegian internal waters.
- Third regulations 1981: Regulations for drilling etc. for petroleum in Norwegian internal waters
- Fourth regulations 1992: Regulations relating to drilling and well activities and geological data collection in the petroleum activities.

In 1997, a standard developed specially to cover the integrity of the wells and it has been known as NORSOK D-010, this standard has been through 4 revisions:

- NORSOK D-010 Rev.1, September 1997
- NORSOK D-010 Rev.2, December 1998
- NORSOK D-010 Rev.3, August 2004
- NORSOK D-010 Rev.4, June 2014
- NORSOK D-010 Rev. 5 (It is planned to be published in the forthcoming months).

It is important to notice that the locomotive of changes in the regulations in Norway was mainly driven and enforced by the industry itself. The industry has contributed effectively in pushing the regulations agenda for the government and establishing relevant standards for the petroleum industry.

“The P&A work of a single well can be divided into three distinct phases: reservoir abandonment, intermediate abandonment and removal of the wellhead and casing strings a few meters below seabed” (Oli and Gas UK, 2011). To make wells permanently plugged, it is not the most attractive activity for the operating companies.

There are thousands of wells in the NCS which are coming to the end of their life cycle after many decades of production. These huge numbers of wells will make the petroleum industry in a position to address the P&A activities in a wider perspective in the next few years. In addition to other concerns related to the environmental impact and the compliance with regulatory and governmental guidelines.

In a statement from the NPD (NPD, 2015), data shows that “there are about 2200 wells used for the production of oil and gas or injection of water and gas to drain reservoirs in the best possible way. It is estimated that approximately 40-50 wells to be plugged per year in the coming years. Most of these wells will be plugged from fixed installations. The numbers change continuously as new wells are drilled and others plugged. It is licensees in the various fields that manages the wells and has an overview of their fields”.

Costs of plugging the remaining wells for the next 40 years will be very large in Norway, as it is estimated to reach 571 billion Norwegian Kroners (NOK). There are totally 5768 wells on the Norwegian Continental shelf, and 2552 wells are remaining to be plugged (Løvås & Ånestad, 2015).

“Wells on the NCS can be classified into two principal categories: those drilled from fixed installations and those drilled from mobile units. About 60% of the wells on the NCS fall into the first category. The remaining 40% also includes wells which are currently inaccessible under (or near) fixed installations and accordingly cannot be plugged until the later have been removed” (Norsk Olje & Gass, 2015).

The latest status from NPD database for wells as per 20. April 2017 contains 6294 wells classified into two different types: -
Development: 4532 wells
Exploration: 1762 wells

I have selected data from the NPD database with status P&A and Plugged. The term P&A is used for exploration wells and development wells when the wells have stopped producing and the field is closed. The status "Plugged" is used when the development well is plugged, but the field is still active. The status for plugged wells are unclear and I have been uncertain if the wells with the status plugged are temporarily or permanently plugged. And we have assumed the releasing of information wells in NPD database are the dates for plugging and abandonment of wells.

From the 6294 wells registered; 1976 is registered "Plugged" status and 1720 is registered with P&A status as shown in Table 1 and Fig. 1.

Table 1: Number of wells by type and status plugged and P&A.

Type	No. of Wells	No. of plugged wells	No. of P&A
Development	4532	5	1442
Exploration	1762	1967	278
SUM	6294	1972	1720

Fig. 1 describes all data available from NPD database and all categories, this thesis focuses only on the category for P&A and Plugged.

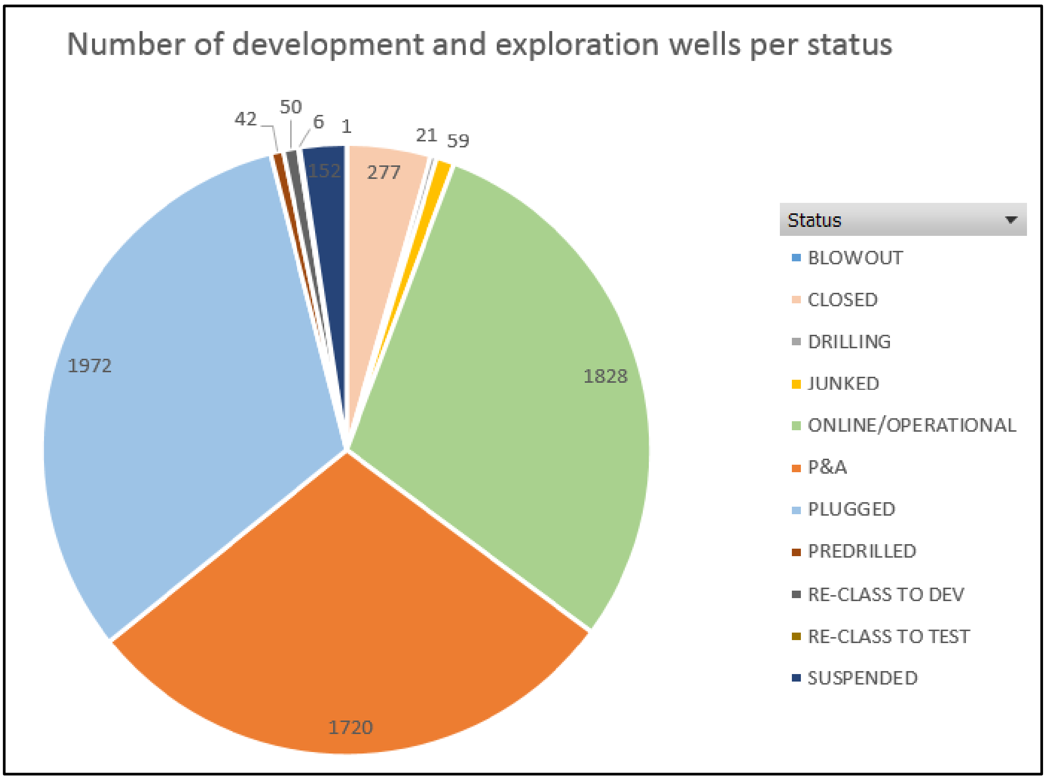

Figure 1: Number of development and exploration wells by status.

Based on NORSOK D-010, the type of wells are categorized based on the requirements and guidelines pertaining to well integrity during different segments of operation as:

a) suspension of well activities and operations;

b) temporary abandonment of wells;

c) permanent abandonment of wells;

d) permanent abandonment of a section in a well (side-tracking, slot recovery) to construct a new wellbore with a new geological well target.

2. Theoretical framework

The study of the theoretical framework is based on reviewing the existing regulations and standards related to P&A in Norway and is based on the experiences from operating companies in the NCS.

Additional intensive literature search carried out on the existing literature available in the field including white papers, University theses and presentation from scientific conferences has been included.

In the earlier stages of the study, I have contacted the Norwegian Petroleum Safety Authorities (PSA) and I have tried to contact all major operators in Norway and had interviews with two companies Statoil and ConocoPhillips to get thorough information on the effect of regulation changes and the scope of P&A within their operations.

A questionnaire has been sent to all major companies that had Plugging operations in NCS (Appendix A), but unfortunately, the responses of these companies were not satisfactory and could not help me to draw a broad conclusion.

The open source data were collected from the NPD from the period of 1967 to 2017 and covered all type of wells in the NCS with all details. The data have been analysed by utilizing the Microsoft Excel package

I have contacted the Petroleum authorities, to gather information on the incidents related to the P&A operations and activities, I have not received any answer in order to analyse the data and trends.

In Norway, the petroleum authorities have defined and developed the necessary regulations for operating the Norwegian continental shelf. These regulations covers both technical and operational to operate safely and not to cause harm to human, environment and assets. The Norwegian regulations are often referring to NORSOK Standards or other wells are known standards as; API, ISO, NOG, IEC, DNV.GL and EN as best recommended standards to fulfil these national requirements.

The international standards are developed in a joint effort from leading operators, companies and other stakeholders in the industry based on the best practice of science and industry. The Norwegian Standards has further developed to comply with the Norwegian context, environment and regulations. The petroleum industry has contributed actively to these developments with allocating resources both competence and financially.

3. Historical development of regulations

The first Petroleum regulation in Norway, the Royal decree of 25th August, relating to Safe Practice, etc. in the Exploration and Drilling for Submarine Petroleum Resources came in 1967. The regulation in its first version was not detailed. The regulations have been changed based on the experiences gained in the later years. Theses updates have been published in the years, 1975, 1981 and 1992 as described in Fig. 2. Norwegian Standard started to issue the first version of the NORSOK D-010 in 1997 followed by three updates later in 1998, 2004 and 2013.

“The regulations for the oil industry started changing significantly in the 1970s when environmental protection became a bigger driver in the regulation of the oil and gas industry” (NPC, 2011). In 2001 the Norwegian petroleum authorities have started to establish some “key regulations relating to health, safety and the environment (HSE) in the offshore petroleum industry and at land-based facilities to make these facilities and operations under the supervisory of the authorities and it was found in two sets of regulations, for HSE and the working environment respectively” (www.ptil.no).

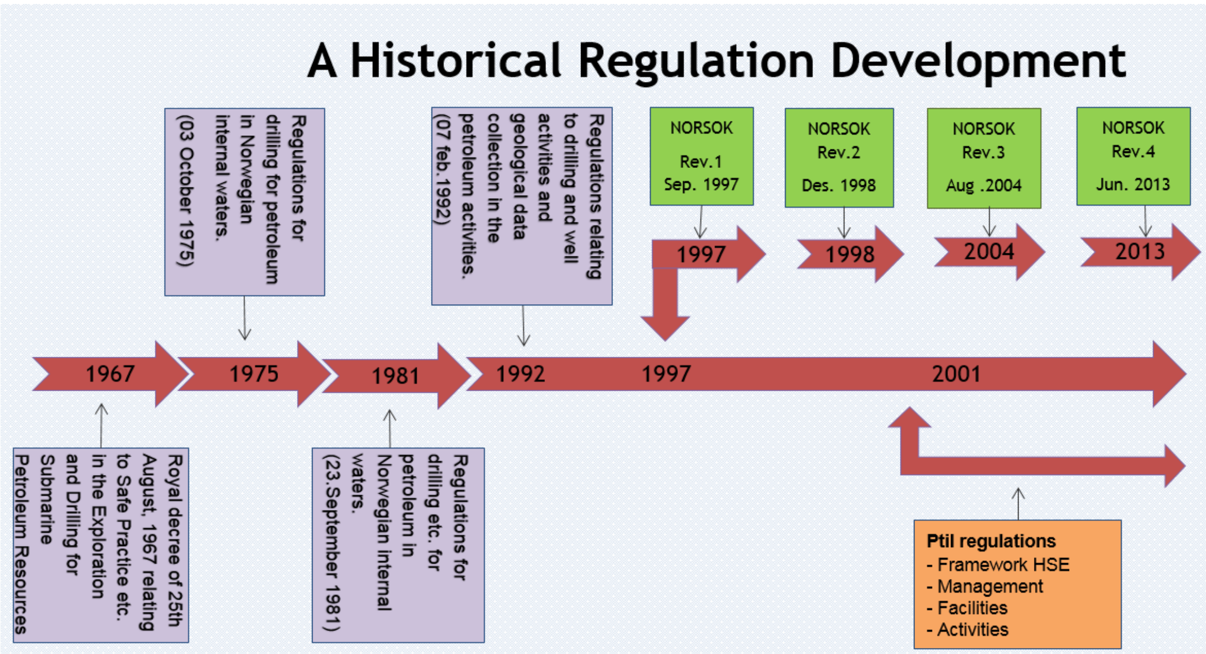

Figure 2: Historical development of plug and abandonment regulations.

The regulation “Royal decree of 25th August 1967” § 64 (Appendix.1) required that “the well cannot be plugged without the authority’s approval. The operators shall apply for the license at least 24 hours in advance of staring operations; they should submit a plan for how the well plugging will be carried out, secured and abandoned.”

According to § 66 for the plugged wells, “the operation shall be performed with a good oilfield practice, with top cement plugs in such a number, of such length and such spacing between the individual plugs. In addition, the compartment between the cement plugs shall be filled with drilling fluid that has the density that can withstand the pressure that may develop in the well".

In the next paragraph, § 67, it is required that "equipment's and installations protruding from the seabed, be removed after the plugging operations are fulfilled and before the well permanently is abandoned. Casing shall be removed to the bottom ensuring no fishing, shipping or other activities can be damaged".

The regulations have no details or specific requirements to the length and positioning of cement plugs. Regulations are referring to industrial experience, practices and guidelines which can be used as a reference.

The next regulation came into force in 1975 and was named "the regulations for drilling for petroleum in Norwegian internal waters". This regulation was more detailed in the description of the ministry for the requirements on the cement plug position with the main changes on the position of the plugs in the well. The new requirements were focusing on dividing according to the zone and the type of wells.

3.1. Open hole

Regarding the location of plugging in an open hole, the regulation of 1975 in §25 part 2.1 required that “the upper and lower part of the plug is located at a minimum of 30 m (100 feet) above and below the zone”. While in the rev 1981 in §9.3.2 and for each individual zone “the cement plug shall be positioned such that its upper and lower ends are located at least 50 m above and below the zone respectively”.

And at the later revision of the regulation in 1992, the requirements have been shortened and more details were added to the cementation guideline. In the cement guidelines §8,1; it has been described that “The minimum height of cement plugs during plugging shall be 100 m. Cement plugs shall extend to at least 50 m from the top of the permeable zone and upwards or 50 m from the potential flow point and upwards”. As mentioned in Fig. 3 this was an additional requirement to the previous versions focusing on the height of cement plug.

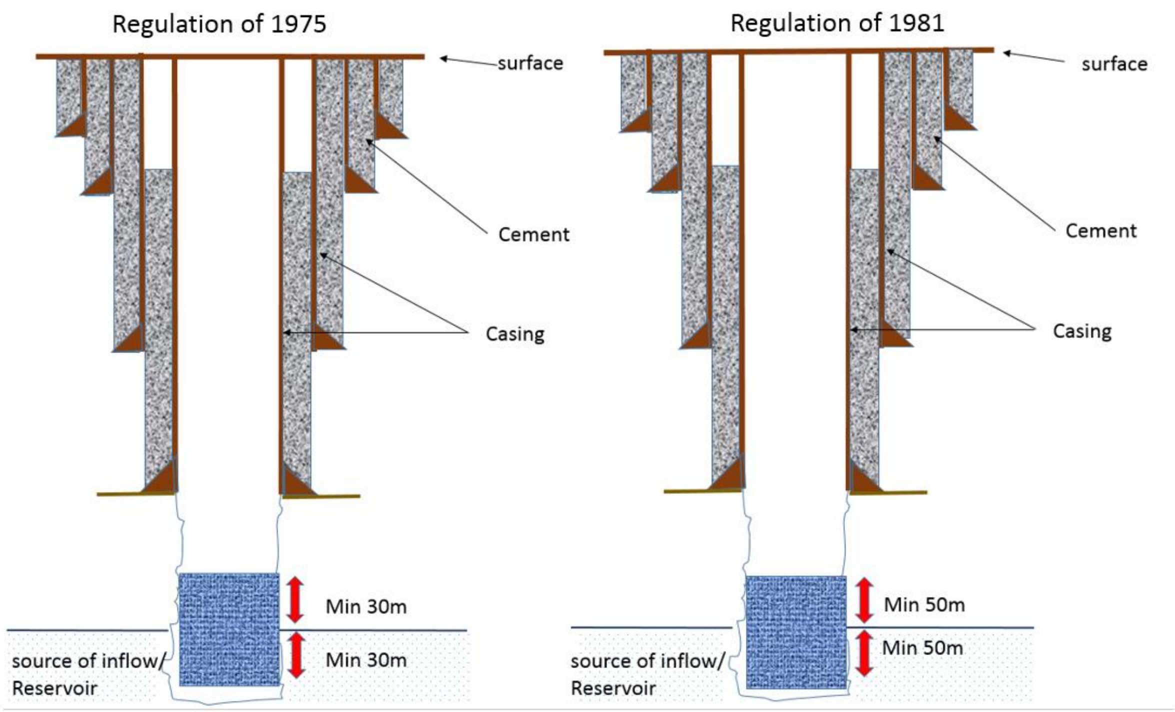

Figure 3: Changes in requirements for open hole

3.2. Open hole below the deepest casing

In the regulation of 1975 § 25 part 2.2. "the cement plug shall be placed in such a manner that it extends a minimum of 30 m above and below the casing shoe", the illustration is shown in Fig. 5. "If the condition of the formation makes cementing difficult a mechanical plug can be positioned in the lower part of the casing, but not more than 50 m above the shoe. Above the said mechanical plug there shall be placed a cement plug of at least 15 m".

Where in the rev 1981 at §9.3.3 there is open hole below the deepest casing, "the cement plug shall be placed in such a manner that it extends a minimum of 50 m above and below the casing shoe. If the condition of the formation makes cementing difficult, a mechanical plug can be positioned in the lower part of the casing, but not more than 50 m above the shoe", the illustration is shown in Fig. 7. Above the said mechanical plug there shall be placed a cement plug of at least 20 m.

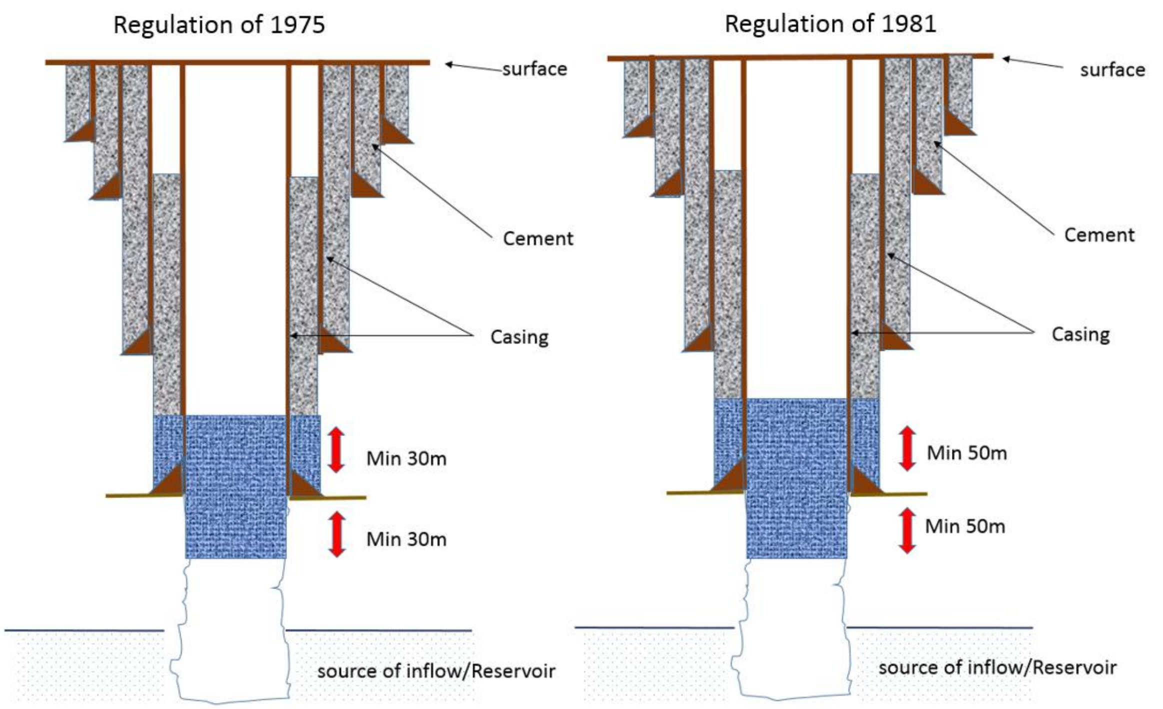

Figure 4: Changes in requirements for open hole below the deepest casing cement plug.

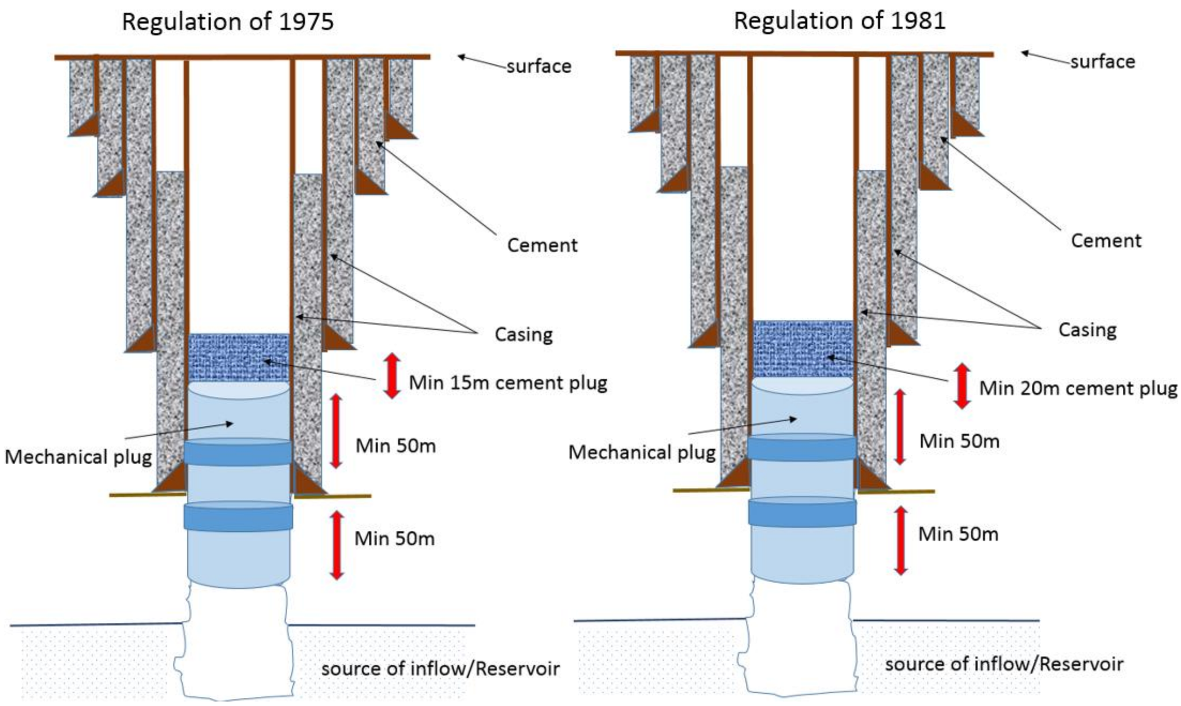

Figure 5: Changes in requirements for open hole below the deepest casing mechanical plug.

3.3. Perforated hole

In1975 regulation § 25 part 2.3 the perforated hole “shall be isolated by means of a mechanical plug and is to be squeeze cemented or a cement plug shall be placed opposite all open perforations extending a minimum of 30 m above and below the perforated interval or down to a casing plug, whichever is less”. In the part of the regulation of 1981 part, 9.3.4 “Perforated zones shall be isolated by means of a mechanical plug and shall be squeeze cemented. If this is not possible”. As shown in Fig. 6, “a cement plug shall be placed in such a way that the upper and lower ends of the plug are located at least 50 m above and below the perforated zone respectively. Or down to the nearest plug if the distance is less than 50 m”.

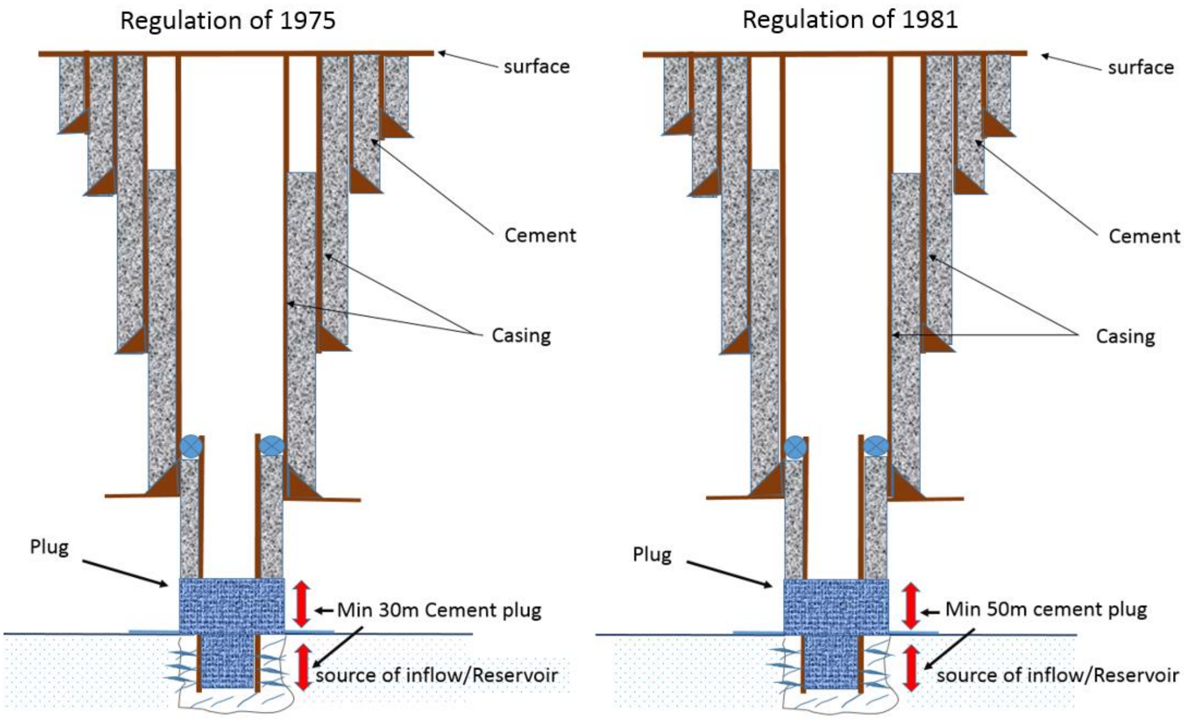

Figure 6: Changes in requirements for perforated well.

3.4. Used Liner

in the regulation of 1975 § 25 part 2.4, “a cement plug shall be placed in such a manner that the plug extends 30 m above and below the point of suspension”. The illustration is described in Fig. 7. In the new revision in 1981 §9.3.5, “a cement plug shall be placed in such a manner that the plug extends 50 m above and below the point of suspension”.

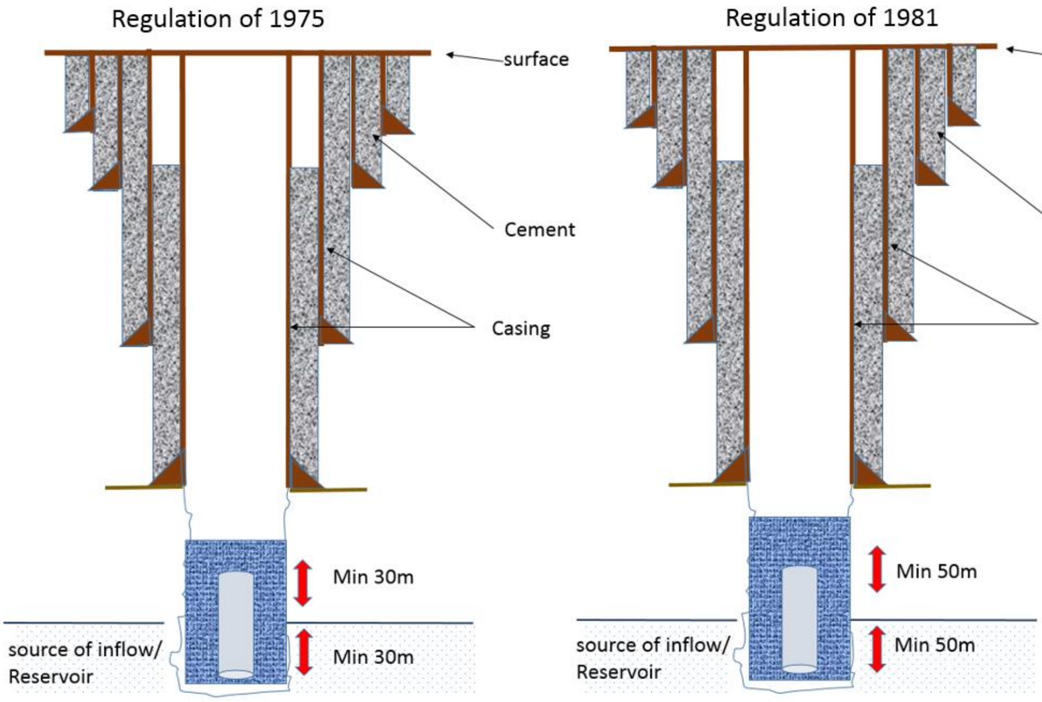

Figure 7: Changes in requirements for the used liner.

3.5. Two sets of casing

In 1975 § 25 part 2.5 “there shall be no communication from the open formation in the drilled hole below to the ocean floor via any annular space between two sets of casing string”. As shown in Fig. 8, “in the cases where the cement is not brought up at least 100 m (300 feet) into previously set string of casing, the last string of casing shall be perforated at the point of the previously set string of casing's shoe and squeeze cemented with a volume at least equal to a cement column of 100 m (300 feet) in the annular space”. No change in the later version in 1992.

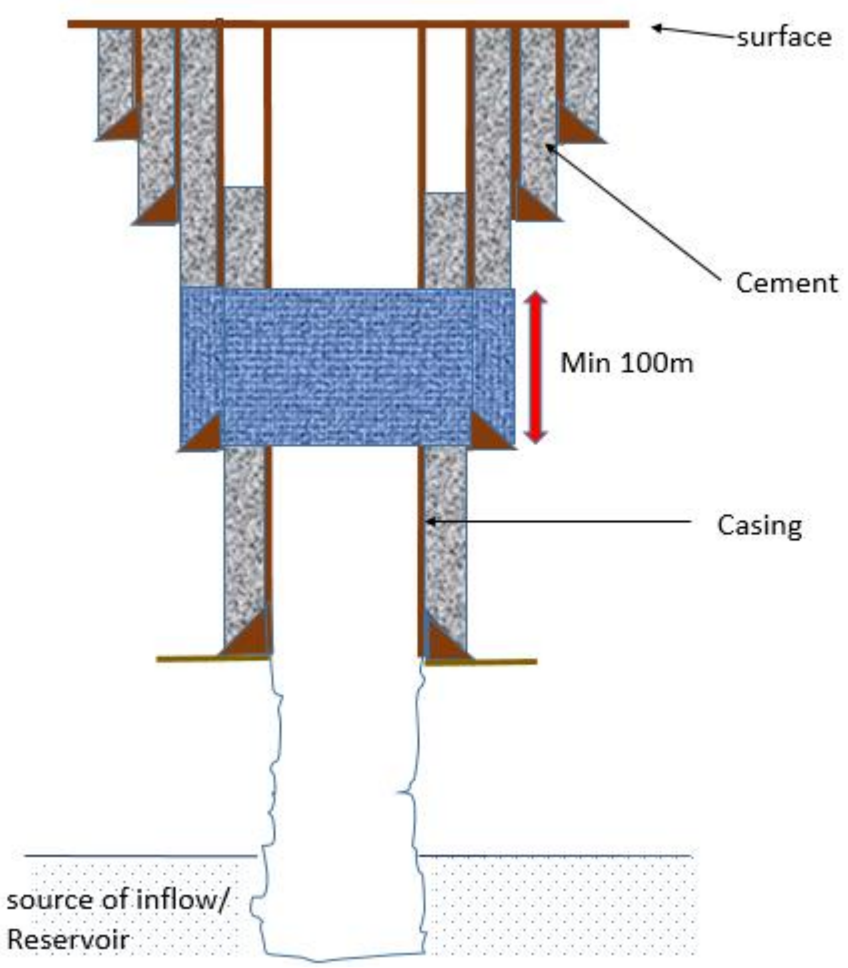

Figure 8: The requirements for two sets of casing.

3.6. String of casing

In 1975 § 25 part 2.6 “a cement plug of at least 30 m shall be placed in the smallest string of casing which extends to the ocean floor. The plug shall be placed at the level of the surface casing shoe” as illustrated in Fig. 9. It is important to mention that this paragraph has been removed and not mentioned in the later revisions in 1981 and 1992.

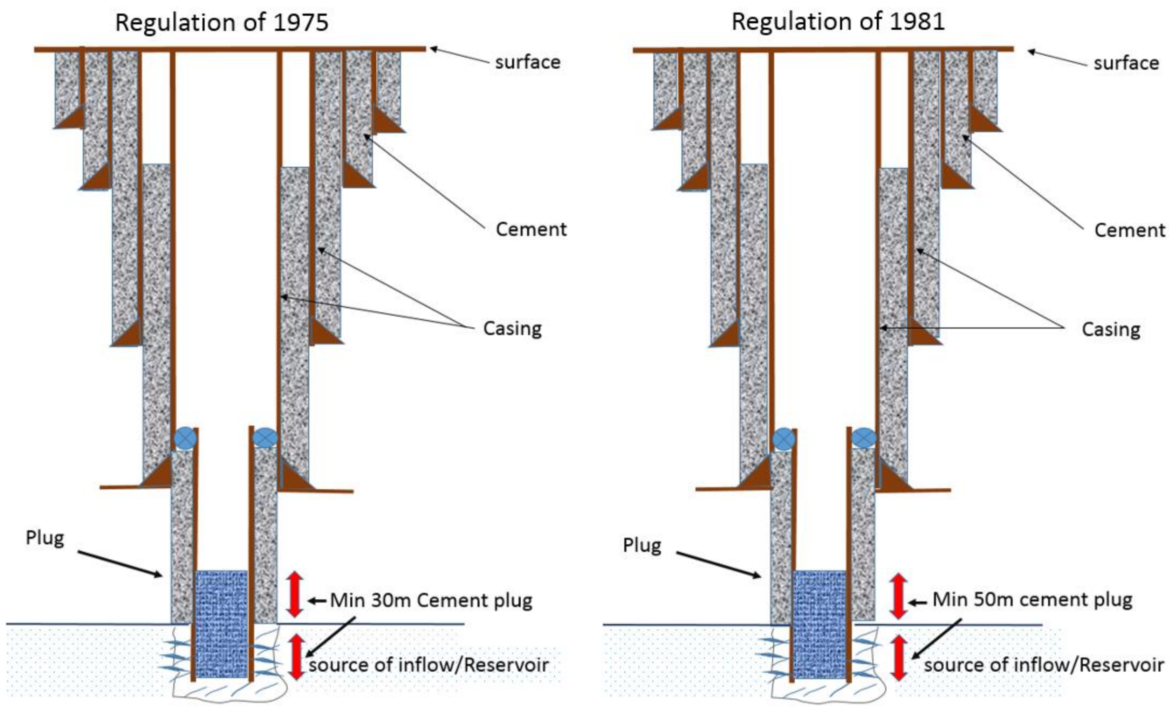

Figure 9: The requirements for the string of casing.

3.7. Top Plug

There are variations of the requirement details in both languages Norwegian and English in 1975 § 25 part 2.7. In the English part, it has been stated that "A cement plug of at least 150 feet, with the top of the plug 150 feet or less below the ocean floor, shall be placed in the smallest string of casing which extends to the surface as it is illustrated in Fig. 10. While in the Norwegian part it has been stated different values. It has been stated that "A cement plug with a minimum 100 m (300 feet) length shall be placed, that the top plug is less than 50 m (150 feet) from the sea bed" In the revision 1992 started new changes until it has been very general as it was earlier in 1967. In 1992 the regulation has started to implement guidelines including the cementation guideline, which was used widely in the petroleum industry.

in 1975 § 25 part 2.8 "the interval between the cement plugs shall be filled with drilling mud or other fluid of sufficient density and with such other properties to safely withstand, together with the plugs, any pressure which may develop within the well". No change in the later versions in 1981 and 1992

We have again small variations in the 2.9, the variation is related to the referral to different Points 1.2 in Norwegian version and 1.4 in the English version. Based on our correspondence with the Norwegian Petroleum Safety Authorities in Norway, the Norwegian version is valid and the English translation is only for help.

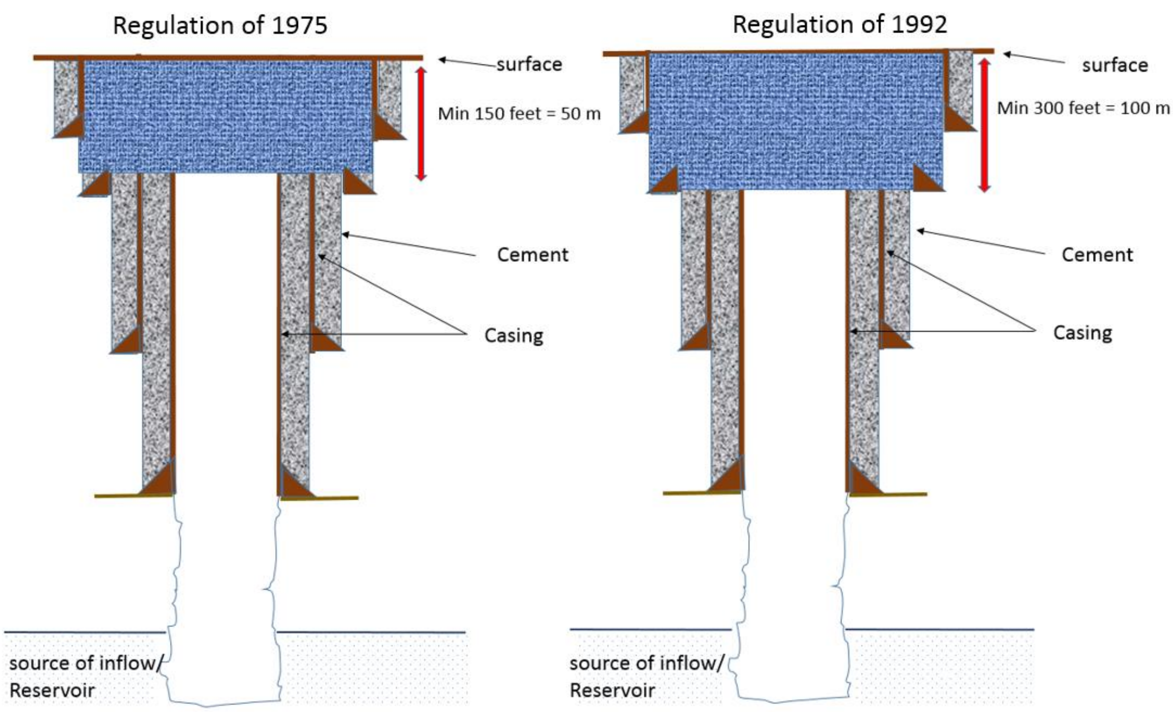

Figure 10: Changes in requirements for top plug.

Table 2: Changes in plug length based on regulatory developments.

Type	Regulation of 1967	Regulation of 1975	Regulation of 1981	Regulation of 1992
Open hole	None	30m	50m	None
Cased hole	None	30m / mechanical not more 50 +15m cement	50m / mechanical not more 50 +20m cement	None
Perforations hole	None	30m	50m	None
Used liner	None	30m	50m	None
In the smallest string	None	30m	None	None
Top plug	None	150feet	100m	None

4. NORSOK D-010

In Norway, Standard Norge has developed a standard for the drilling and well operations and gave it a particular number called NORSOK D-010. The first version of the NORSOK D-010 was published in September 1997. In this version, the issues related to P&A were not highlighted in part 5.4.9 on Cement plug barrier it is stated that “a cement plug being part of an abandonment program shall extend a sufficient length above the highest leak passage”.

One year after the first version of NORSOK D-010 (Rev.1), in 1998, NORSOK D-010 (Rev.2) was released. In this revision, additional explanations and details covering all other parts related to the P&A operations and requirements have been added. The well was divided in relation to the located areas or well parts; open hole, with liner and perforated well.

In 2004, Rev.3 was published. In this revision, the requirements were not changed but developed into fixed tables that are referred to from different parts of the standard. For easier understanding and more visualization, the schematics have also been developed to show and explain each part of the well in details.

The Permanent Abandonment section refers to 2 tables as Table 22 and Table 24 in NORSOK D-010 Rev.3. In those two tables, the minimum requirements for casing cement and cement plug are defined and explained. The cement plug height requirements changed from meter to meter measured depth.

The new version of the NORSOK D-010 has emphasized that “well barriers should be installed as close to the potential source of inflow as possible, covering all possible leak paths”.

More information is added to the rev. 3 of the NORSOK D-10 with regard to the ”primary and secondary well barriers shall be positioned at a depth where the estimated formation fracture pressure at the base of the plug is in excess of the potential internal pressure”. And it has been stated that “the final position of the well barrier/WBEs shall be verified” (NORSOK D-010).

The incident of Deepwater Horizon oil spill (Macondo) in the Gulf of Mexico on 20th April 2010 has been a trigger for strengthening the well integrity and plugging and abandonment requirements and regulations around the world. In Norway, the rev. 4 of NORSOK was updated in 2013. In this revision, it has been more focus on visualization of wells in details and new topics has been added to the standard as a section milling and PWC.

The elements in the changes and updates in the NORSOK D-010 standard has been detailed in Table 3.

Table 3: Changes in NORSOK D-010.

Type	NORSOK D-010 (Rev.2) in 1998	NORSOK D-010 (Rev.3) in 2004	NORSOK D-010 (Rev.4) in 2013
Open hole	100 m length of cement. 50 m from potential	It shall extend minimum **50 m** MD above any source of inflow/ leakage point.	**100 m** MD with minimum 50 m MD above any source of inflow/leakage point.
Cased hole	None	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.	**50** m MD if set on a mechanical/ cement plug as foundation, otherwise **100 m** MD
Transition	None	A plug in transition from open hole to casing should extend at least **50 m** MD below casing shoe.	A plug in transition from open hole to casing should extend at least **50 m MD** above and below casing shoe
Perforations hole	minimum of **100** m above the top perforations. If the distance between the test intervals is less than **100 m** thus making a **100 m** cement plug impossible, a mechanical packer should be set as close to the top of the perforations as possible. Minimum of **10m** cement shall be left on top of the squeeze retainer.	None	None
Used liner	Minimum **50** m from above and below the liner top.	A casing/ liner with shoe installed in permeable formations should have a **25** m MD shoe track plug.	A casing/liner shall have a shoe track plug with a 25 m MD length.
Cut and pull of casings	The minimum height of a cement plug shall be **100 m**. Cement plugs shall extend minimum 50 m from the top of a permeable zone and upwards, or **50 m** from a potential flow point and upwards.	None	None
Top plug	The surface cement plug shall be minimum **200** m in length and the top of the cement shall run no deeper than 50 m below the seabed.	None	50 m MD if set on a mechanical plug, otherwise 100 m MD.

Section milling to establish a cement plug

The schematic section milling to establish a cement plug and alternative method to establish a permanent well barrier as shown in Fig. 11 and Fig. 12 in two alternative methods. The requirements for section milling has been added in Rev. 4. If the cement quality behind a casing is poor, then there is a need to remove casing and cement. One method of doing this is section milling.

The following example can be applied when section milling is required to establish well barriers.

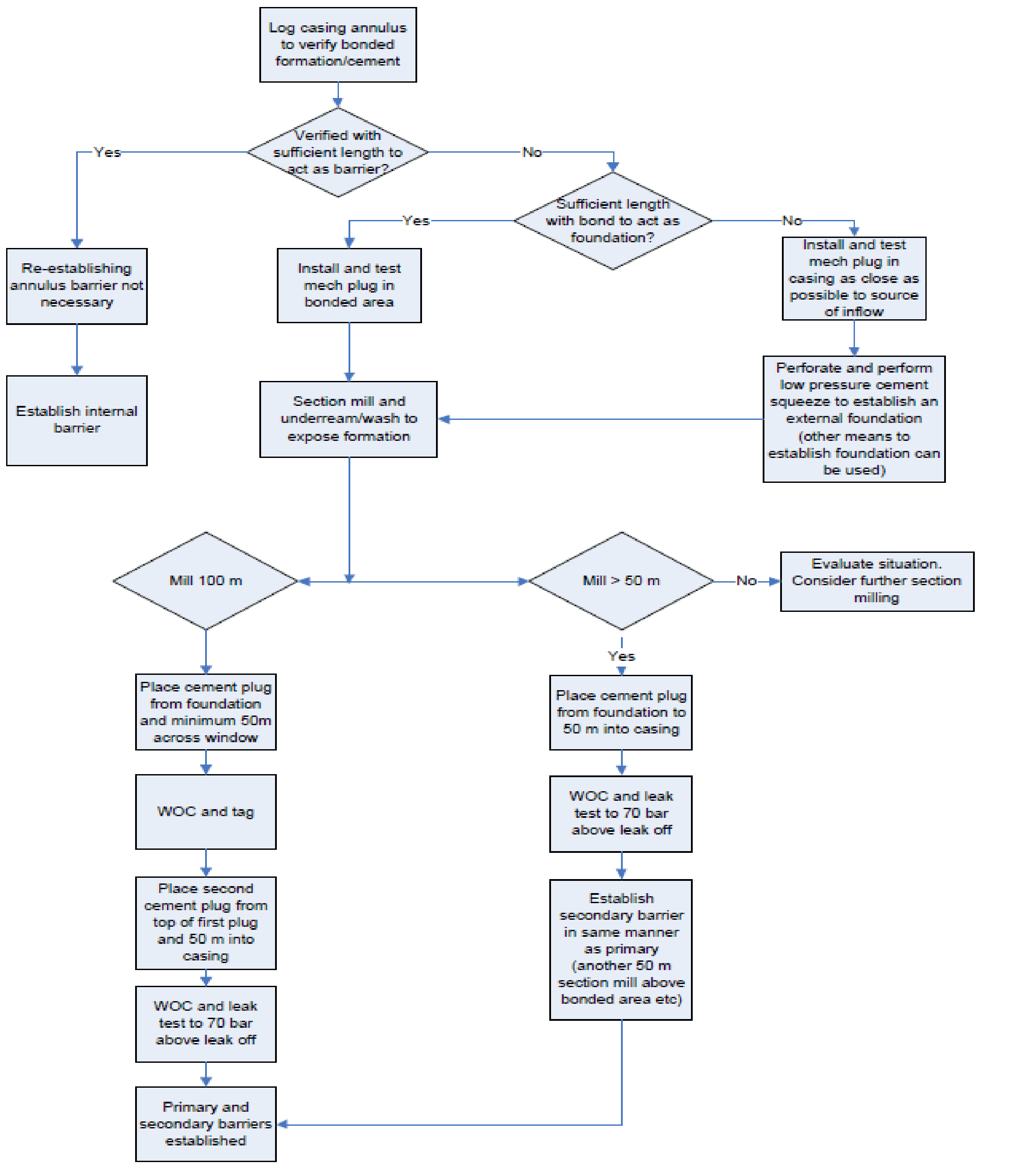

Figure 11: Section milling to establish a cement plug.

Alternative method to establish a permanent well barrier

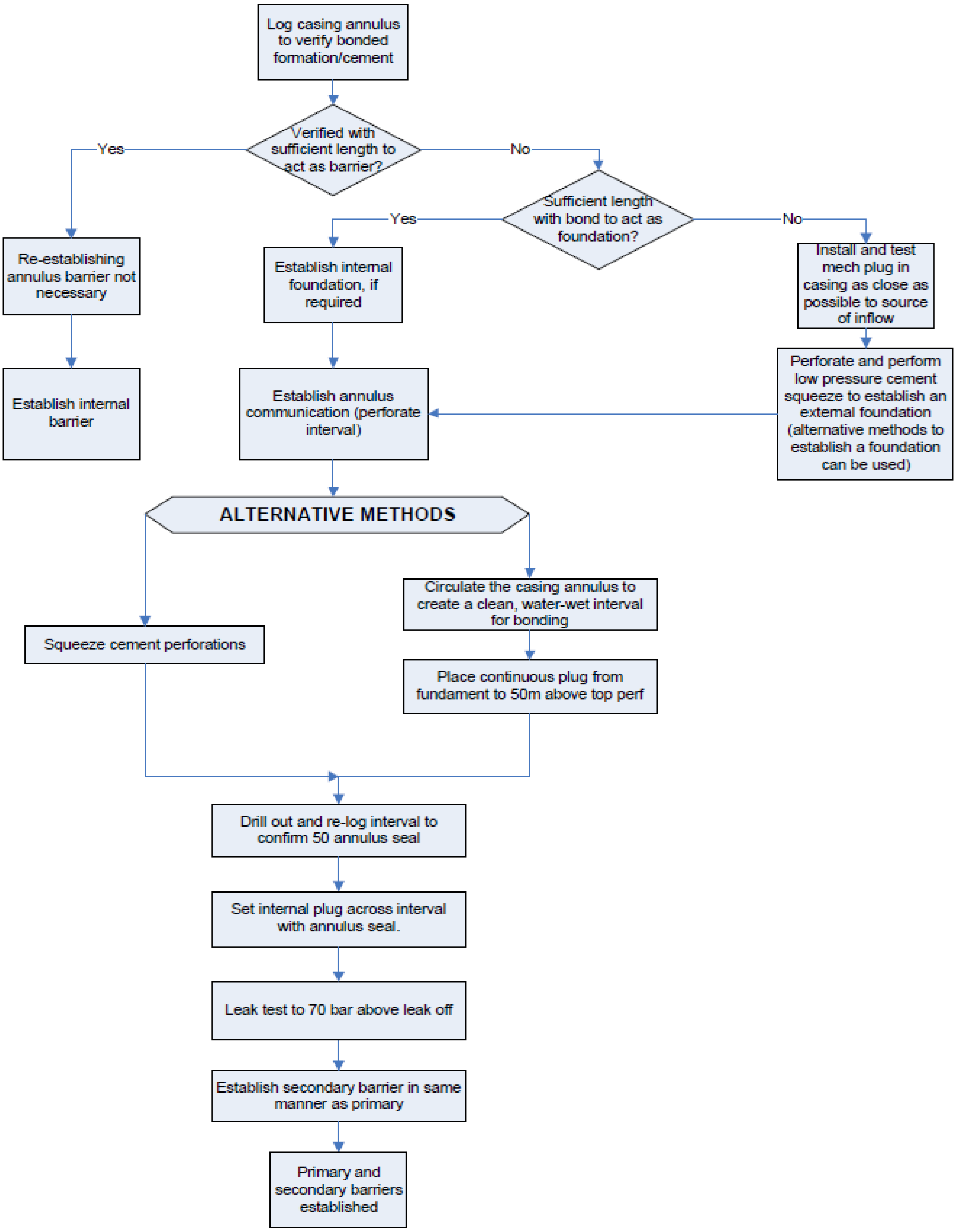

Figure 12: Alternative method to section milling for establishing a permanent well barrier.

5. Barriers

Barriers are any physical and/or non-physical elements planned or placed to prevent, reduce or control undesired events or accidents. The barriers can be placed as a single barrier or at multiple levels and sequences as it is shown in Fig. 13 for barrier diagram. Barriers are important for normal established systems as well as complex socio-technical systems. The barriers can be categorized as technical and non-technical barriers such as Operational and organisational barriers. The barriers can be classified based on functions required to perform, in order to prevent occurrence of undesirable events.

There are various definitions of the barriers in the industries. In the last revision of the Norwegian Petroleum authorities' barrier note in March 2017, they have defined the barriers as; "Activity that has an objective either to identify the status that can lead to failure, hazards or accident situations, preventing that a concrete event to occur or to develop to affect the event to the intentional direction or limit damages and/or loss" (PSA, 2017).

The Norwegian management regulation Section 5 on barriers is emphasizing that "the barriers shall be established that at all times can:

a) identify conditions that can lead to failures, hazard and accident situations,
b) reduce the possibility of failures, hazard and accident situations occurring and developing,
c) limit possible harm and inconveniences".

The regulations guidelines stating that the technical barrier elements means; equipment and systems that are included in the realisation of a barrier function. The performance of the barriers should be verified in accordance to, inter alia, capacity, reliability, accessibility, efficiency, ability to withstand loads, integrity and robustness at all phases of the operation, this should cover the whole life cycle of the well, installation and the field.

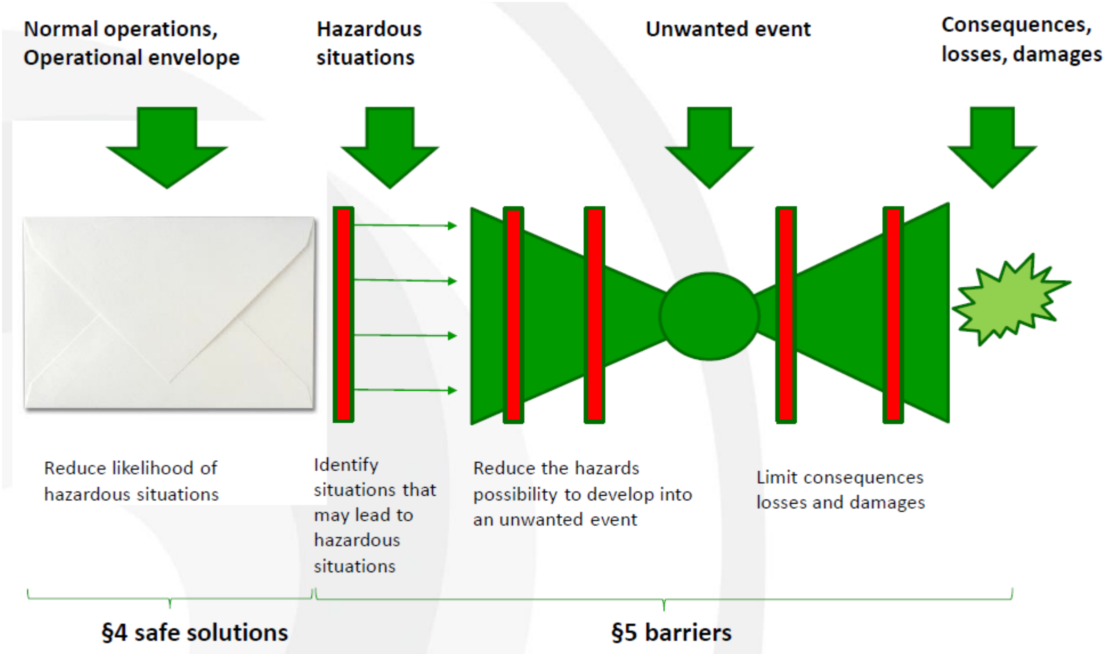

Figure 13: barrier Diagram. (Lootz & Ersdal, 2016)

Barriers can be categorized into three main categories, these are; technical, operational and organizational barriers. Each of these categories has their elements that individually or in combination will affect the result of the event. The barriers can be placed in sequences; primary barrier, secondary barrier and further on as it is described in Fig. 14 for recovering the oil spill incident. The barriers mainly contribute to reducing the possibility of specific errors, accidents and emergencies occur, or restricting or preventing damages/losses/ disadvantages.

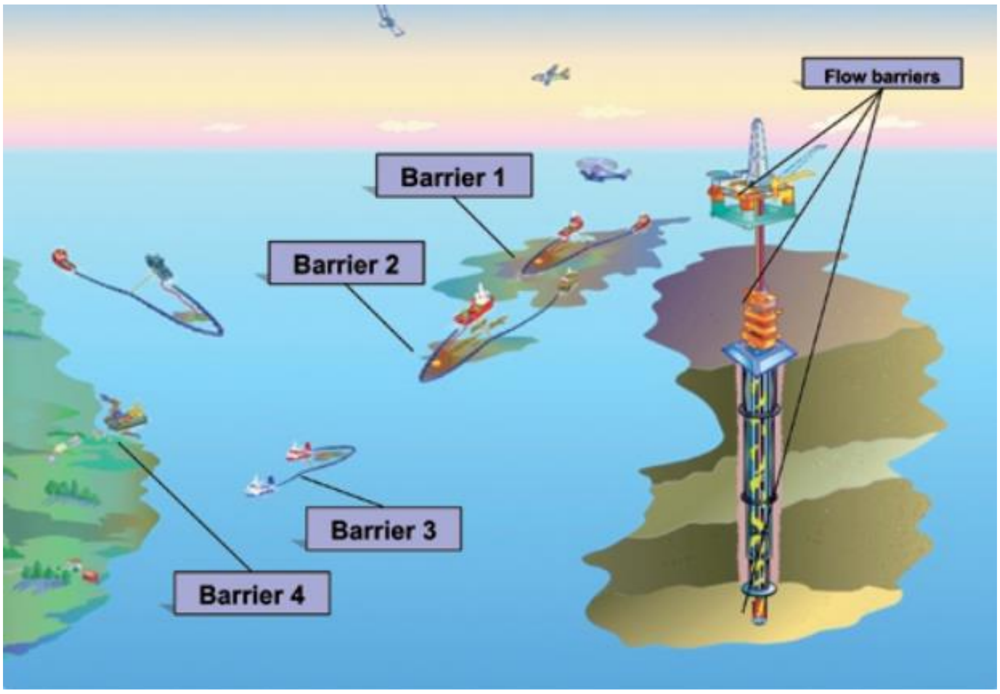

Figure 14: Various types of barriers. (MOE, 2009)

"Each barrier element has defined performance requirements; these requirements shall ensure that the requirements are performing their functions in an effective manner and they are:

- Capacity
- Functionality
- Effectiveness
- Integrity
- Reliability
- Availability
- Survivability
- Robustness
- Competence of operators and technical personnel, and
- Response- and mobilization time". (PSA, 2017)

5.1. Well Barriers

The petroleum regulations in Norway on P&A operations are mainly described in the following sections:

- §48 – Well Barriers in the facilities regulations.
- §85 – Well Barriers in the activities regulations.
- §88 – Securing Wells in the activities regulations:

§48 – Well Barriers in the facilities regulations states "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 "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 "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."

According to NORSOK D-010 Rev.4 well barriers are defined as an envelope of one or several well barrier elements preventing fluids from flowing unintentionally from the formation into the wellbore, into another formation or to the external environment.

As it has been stated in the Standard, the well barriers shall be defined prior to the commencement of an activity or operation by identifying the required well barrier elements (WBE) to be in place, their specific acceptance criteria and monitoring method.

The well barrier element as shown in Fig. 16 is a physical element which in itself does not prevent flow but in combination with other WBE's forms a well barrier. For these well barrier elements, it has been defined the acceptance criteria that requires; Technical and operational requirements and guidelines to be fulfilled in order to verify the well barrier element for its intended use.

When a WBE has been installed, its integrity shall: (NORSOK D-010 Rev.4)

a) be verified by means of pressure testing by application of a differential pressure; or
b) when a) is not feasible, be verified by other specified methods.

Well barrier elements that require activation shall be function tested.

A re-verification should be performed if:

a. the condition of any WBE has changed, or;
b. there is a change in loads for the remaining life cycle of the well (drilling, completion and production phase).

DNV.GL has established a guideline/recommended practice. Presented in Fig. 15 from DNVGL-RP-E103, "the aim of the document is to provide a risk-based framework for well abandonment design and permanent". The document describing "a risk-based approach to be applied in connection with the context of each well and to be a suitable solution for each individual well characteristics. This is due to the fact that the other requirements are prescriptive more general requirements to all type wells". As stated in the guideline "the guideline will allow cost-saving benefits to be gained from the least critical wells".

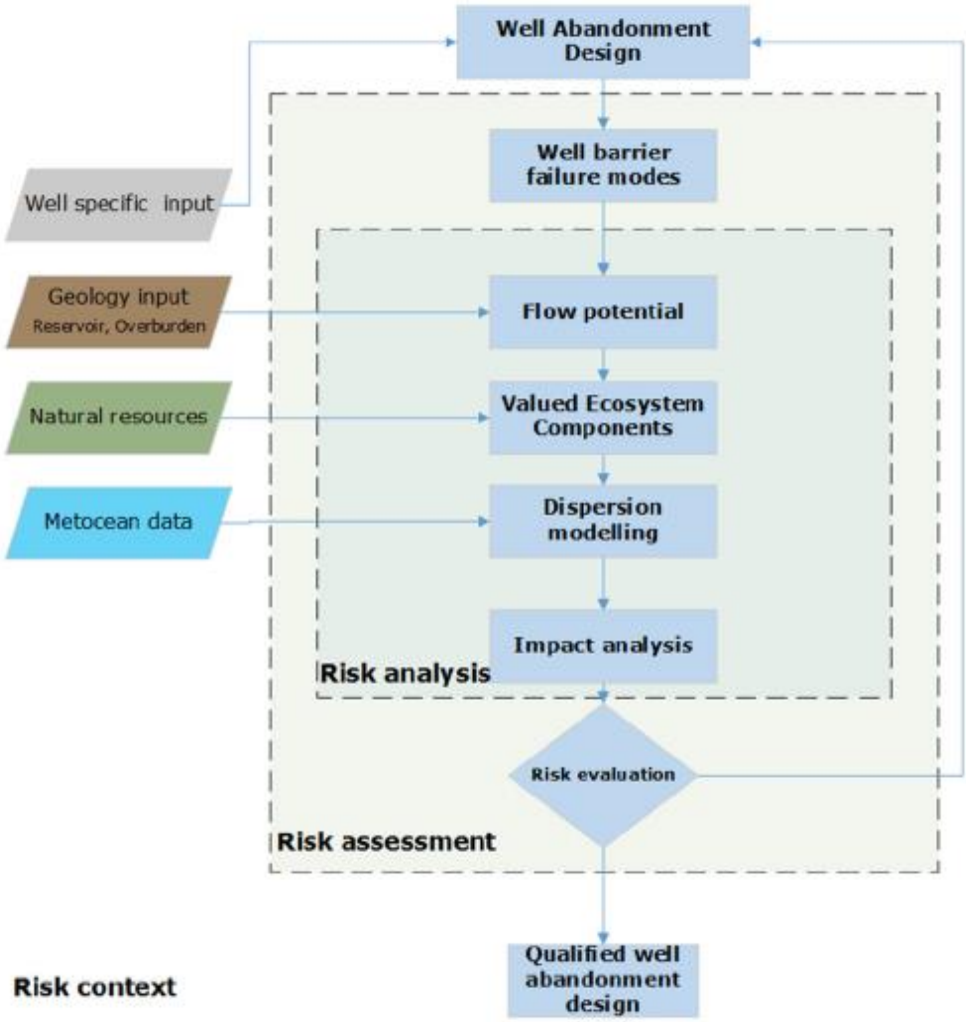

Figure 15: Elements in well abandonment risk assessment. (DNV.GL Guideline rev.2016)

The Guideline as shown in Fig. 15 recommending that "the permanent well barrier design should be fit-for-purpose and take into account the effects of any reasonably foreseeable chemical and geological process. Its function should be to control hydrocarbon-bearing formation(s) with moderate or significant flow potential. The duration of the requirement for the permanent well barrier should be site specific and should be dependent on the well barrier's design functionality" (DNV.GL Guideline rev.2016).

The permanent well barriers and well barrier elements as illustrated in Fig. 16 "should be installed at a depth where the formation is strong enough to contain the hydrocarbon-bearing formations" (DNV.GL Guideline rev.2016).

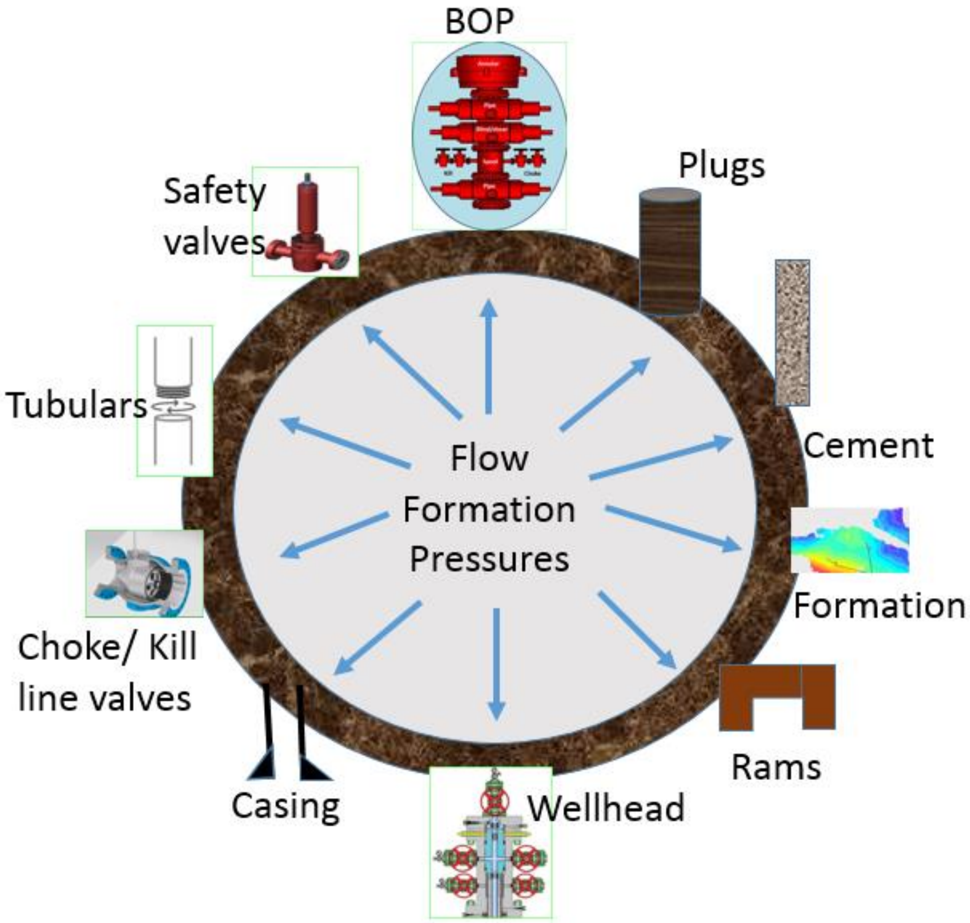

Figure 16: Well barrier elements.

In general, it can be summarised that well barriers should be designed, selected and/or constructed such that (Aguilar et al., 2016):

- They can withstand the maximum anticipated load and differential pressure they may become exposed to, including multiaxial loads, environmental conditions during planned and potentially extreme situations, as agreed with stakeholders.
- They can be leak- and function-tested or verified by other methods.
- No single failure of a well barrier envelope (a combination of well barrier elements) leads tp uncontrolled flow of fluids or gasses from the formation to the surface.
- Re-establishment of a lost well barrier or another alternative well barrier can be done.
- They can operate competently and withstand the environment for which they may be exposed to over time as required by contract and as agreed with all stakeholders.
- Their physical location and integrity status is known at all times when such monitoring is possible and contractually provided for.
- In compliance with the requirements the respective well barrier element acceptance criteria (WBEAC).

Table 4: P&A well barrier requirements/ recommendations described in the main standards.

DNV.GL Recommended practice:	NORSOK D-010:	Norwegian oil and Gas Association Guideline:
A permanent well barrier is a combination of one or several well barrier elements (WBE's) that contain fluids within a well to seal a source of inflow P&A is an action taken to ensure permanent isolation of fluids and pressures from exposed permeable zones along well trajectory by the installation of well barriers	A permanent well barrier should have the following characteristics:	Wells which are under construction or permanently plugged and abandoned are not covered by this guideline.
withstand the maximum anticipated combined loads to which it can be subjected	a) provide long-term integrity (eternal perspective);	
Function as intended in the environments (pressures, temperature, fluids, mechanical stresses) that can be encountered throughout its entire life cycle, and	b) impermeable;	
Prevent unacceptable hydrocarbon flow to the external environment.	c) non-shrinking;	
	d) able to withstand mechanical loads/impact;	
	e) resistant to chemicals/ substances (H2S, CO2 and hydrocarbons);	
	f) ensure bonding to steel;	
	g) not harmful to the steel tubulars integrity.	

5.2. Well barrier acceptance criteria

"Permanently abandoned wells shall be plugged with an eternal perspective considering the effects of any foreseeable chemical and geological processes. The eternal perspective with regards to re-charge of formation pressure shall be verified and documented" (NORSOK D-010, Rev.4).

Table 5: Well barrier depth position (ref. NORSOK Table 24)

Name	Function	Depth position
Primary well barrier	To isolate a source of inflow, formation with normal pressure or over-pressured/ impermeable formation from surface/seabed.	The base of the well barriers shall be positioned at a depth were formation integrity is higher than potential pressure below, see 4.2.3.6.7 Testing of formation.
Secondary well barrier	Back-up to the primary well barrier, against a source of inflow	As above
Crossflow well barrier	To prevent flow between formations (where crossflow is not acceptable). May also function as a primary well barrier for the reservoir below.	As above
Open hole to surface well barrier	To permanently isolate flow conduits from exposed formation(s) to surface after casing(s) are cut and retrieved and contain environmentally harmful fluids. The exposed formation can be over-pressured with no source of inflow. No hydrocarbons present.	No depth requirement with respect to formation integrity

The chosen formation integrity test method shall be determined by the objective of the test. The most common methods are:

Permanently plugged wells shall not be left for ever perspective. Therefore, the long-term effects for both chemical and geological processes must be evaluated.

The well plugging schematic is illustrated in Fig. 17. As it is defined in the NORSOK D-010, a permanent well barrier should have the following characteristics (NORSOK D-010 Rev.3):

a) provide long-term integrity (eternal perspective);
b) impermeable;
c) non-shrinking;
d) able to withstand mechanical loads/impact;

e) resistant to chemicals/ substances (H_2S, CO_2 and hydrocarbons);

f) ensure bonding to steel;

g) not harmful to the steel tubulars integrity.

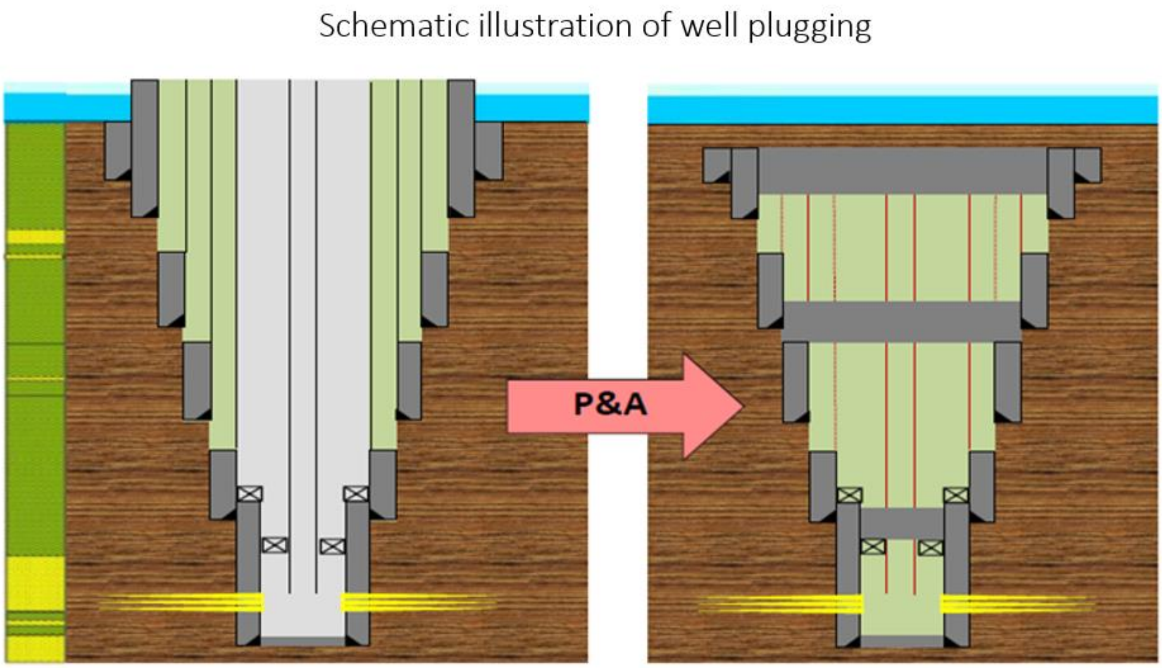

Figure 17: Schematic illustration of well plugging. (Torsæter, 2017)

“The tubular steel is not an acceptable permanent well barrier unless it is supported by cement (inside and outside)” (NORSOK D-010 rev.3).

“The Permanent well barriers is straddling over the entire cross section of the well, In the position where it includes all annulus and seals both vertically and horizontally” (Abshir et al., 2012) see Fig. 18. “The process of barrier setting should be verified and assured that the cement on the outside of the casing is sealed before inserting it into a cement plug in the casing to assure the safety and to prevent the flow of oil, gas and other liquids out of the well” (NORSOK D-010 rev.3).

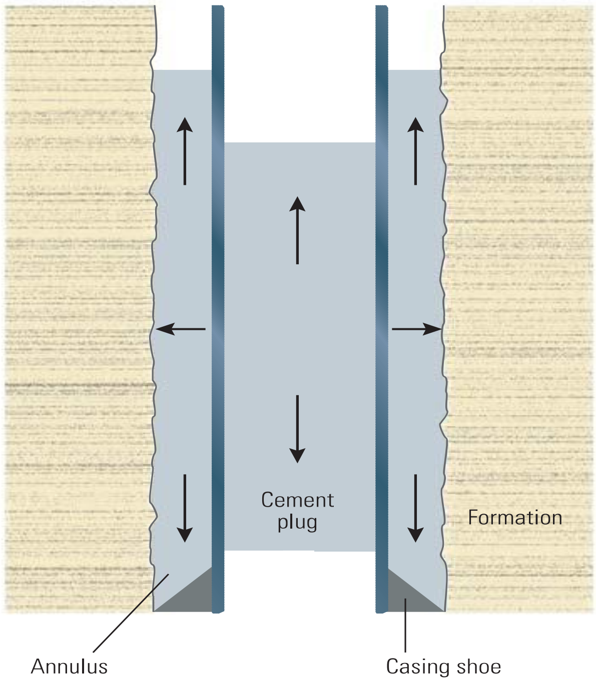

Figure 18: Permanent well barrier. (Abshir et al., 2012)

The Norwegian oil and gas association has developed a guideline for well integrity in 01.10.2008; the Guideline No 117 titled as “the Norwegian oil and gas recommended guidelines for well integrity”. The guideline has undergone several updates the last revision (Rev. 5) is updated on 16.08.2016 (Norsk Olje & Gass, 2016).

The Norwegian Oil and Gas Association recommended guidelines for Well Integrity rev. 5, August 2016. The guideline describes that the “Technical standards that are applicable can be of several different origins:

- Recognised industry standards (API, ISO, etc.)
- National standards (NORSOK etc.)
- Company specific standards
- Supplier specific standards” (Norsk Olje & Gass, 2016).

The §5.2.2 in guideline defining the well barriers and stating that “the well barrier shall be designed to prevent unintentional influx, cross flow to shallow formation layers and outflow to the external environment, and so that they do not obstruct ordinary well activities” (Norsk Olje & Gass, 2016) in order to safe barrier setting and avoiding any failure that lead to undesired safety a events as blowout.

Furthermore, the guideline determining that “the state and performance of the well barriers should be verified to assure the functionality of the barriers at all times when establishing of monitoring and verification activities are possible” (Norsk Olje & Gass, 2016).

The “Norwegian oil and gas association” guideline as all other standards is focusing on the independency between the barriers. It is stated that “If common elements exist, a risk analysis shall be performed and risk reducing/mitigation measures applied to reduce the risk ALARP” (Norsk Olje & Gass, 2016).

6. Data collection

The major operating companies have been contacted to gather the necessary information and data. I was lucky to get meeting with the key person working with P&A in Statoil and ConocoPhillips. In addition, I have sent a questionnaire (Appendix A) to most of the operator companies on the NCS, these companies were:

- Aker BP.
- ConocoPhillips
- ENI Norge
- Statoil
- Total
- Centrica
- ExxonMobil
- ENGIE
- Hess
- Repsol
- Winter shell
- Faroe Petroleum
- Norsk shell

I have received the answer only from 4 companies; Eni, ConocoPhillips, Shell and Statoil.

The database from NPD on the wells contains information on three type of wells categorised as exploration, development and other types of wells.

The information is gathered from all oil and gas companies for the periods from 1967 until now. The date is registered with the name of companies in the similar period. Many of these companies have changed names, merged or acquired by other companies. In order to collect and analyse the data and its effects with have classified the data based on the current name of the operating companies as defined the Table 6.

Table 6: List of operators on the NCS.

Current Company name	Other company names
A/S Norske Shell	-
Aker BP ASA	BP Amoco Norge AS, Pertra AS (OLD), Det norske oljeselskap ASA (old), Det norske oljeselskap ASA, BP Petroleum Dev. of Norway AS, BP Norway Limited U.A., BP Norge AS, Amoco Norway Oil Company,
BG Norge AS	-
Centrica Resources (Norge) AS	-
Chevron Texaco Norge AS	-
ConocoPhillips Norge	Phillips Petroleum Norsk AS, Phillips Petroleum Company Norway, Norske Conoco A/S, ConocoPhillips Skandinavia AS, ConocoPhillips Norge, Conoco Norway Inc.,
Deminex Norge AS	-
DONG E&P Norge AS	-
E.ON E&P Norge AS	E.ON Ruhrgas Norge AS
Edison Norge AS	-
ENGIE E&P Norge AS	GDF SUEZ E&P Norge AS,
Eni Norge AS	Norsk Agip AS,
ExxonMobil Exploration and Production Norway AS	Mobil Exploration Norway INC, Esso Exploration and Production Norway A/S,
Faroe Petroleum Norge AS	-
Hess Norge AS	Amerada Hess Norge AS
Idemitsu Petroleum Norge AS	-
LOTOS Exploration and Production Norge AS	-
Lundin Norway AS	-
Maersk Oil Norway AS	-
Marathon Oil Norge AS	Marathon Petroleum Norge AS
Nexen Exploration Norge AS	-
Noil Energy ASA	-
Noreco Norway AS	-
Norsk Chevron AS	-
Norske Murphy Oil Company	-
Norwegian Energy Company ASA	-
Norwegian Gulf Exploration Company AS	-
OMV (Norge) AS	-
Paladin Resources Norge AS	-
Petro-Canada Norge AS	-
Premier Oil Norge AS	-

Repsol Exploration Norge AS	Repsol Norge AS
Revus Energy ASA	-
Rocksource	Rocksource Exploration Norway AS, Rocksource ASA
RWE Dea Norge AS	-
Statoil Petroleum AS	StatoilHydro Petroleum AS, StatoilHydro ASA, Statoil Petroleum AS, Statoil ASA (old), Saga Petroleum ASA, Norsk Hydro Produksjon AS, Den norske stats oljeselskap AS,
Suncor Energy Norge AS	-
Syracuse Oils Norge A/S	-
Talisman Energy Norge AS	-
Texaco Exploration Norway AS	-
Total E&P Norge AS	Total Fina Elf Exploration Norge AS, Total Norge AS, Total E&P Norge AS, Fina Production Licenses AS. Elf Petroleum Norge AS, Elf Norge A/S, Elf Aquitaine Norge A/S
Tullow Oil Norge AS	-
Unocal Norge A/S	-
VNG Norge AS	VNG Norge (Operations) AS
Wintershall Norge ASA	-

There are many actors in the field of exploration, drilling and development of oil and gas fields in Norway. Fig. 19 shows the majority of these operators who are operating the wells with different scales and volumes.

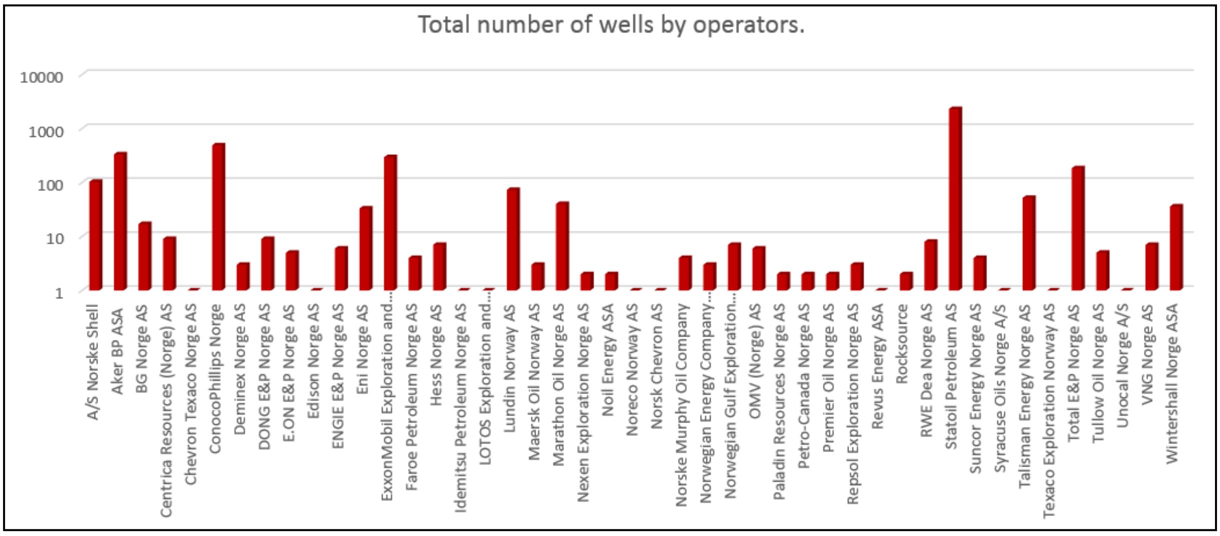

Figure 19: Total number of wells by operators.

Fig. 20 shows the total number of wells with the status of P&A by the major operators. Statoil is the largest operator in the field and followed by ConocoPhillips, Total E&P, ExxonMobile and Aker BP.

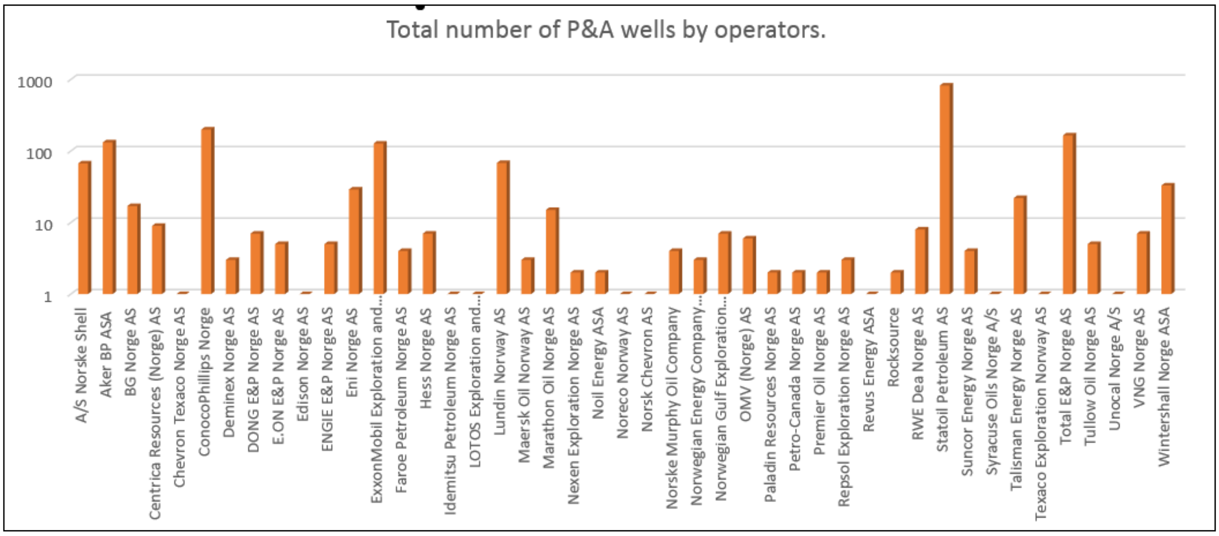

Figure 20: Total number of P&A wells by operators.

Fig. 21 shows the total number of wells with the status plugges by the major operators. Statoil is the largest operator in the field and followed ConocoPhillips, ExxonMobile, Aker BP, Marathon, Talisman Energy, Total E&P and Norsk Shell.

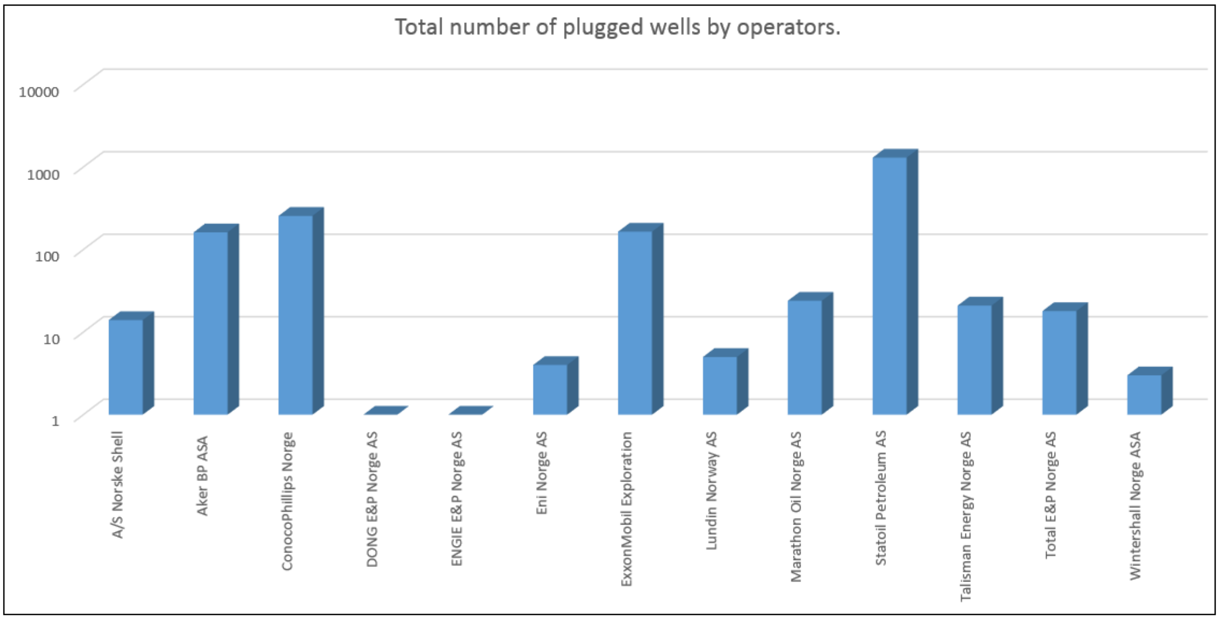

Figure 21: Total number of plugged wells by operators.

The Norwegian continental shelf consists of the tenth of fields for exploration or production of oil and gas, these fields are in the various level of maturity and development. Fig. 22 shows the majority of these fields with different scales and volumes. Troll is largest with 658 wells followed by EKOFISK 376 and Statfjord 368.

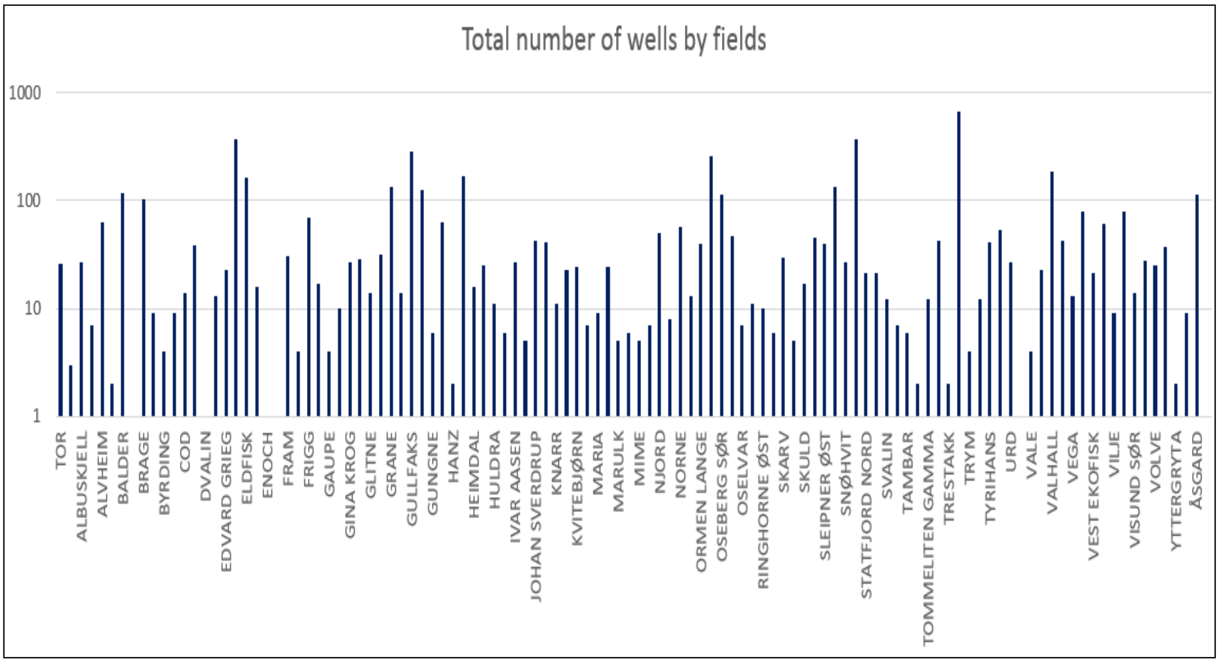

Figure 22: Total number of wells by fields

Table 7: Number of wells with P&A status per year by types.

Regulations	Year	Exploration	Development	Total (P&A)
Royal decree of 25th August 1967 relating to Safe Practice etc. in the Exploration and Drilling for Submarine Petroleum Resources	1967-1974	75	4	79
Regulations for drilling for petroleum in Norwegian internal waters.	1975-1980	114	61	175
Regulations for drilling etc. for petroleum in Norwegian internal waters	1981-1991	381	87	468
Regulations relating to drilling and well activities and geological data collection in the petroleum activities	1992-1996	170	45	215
NORSOK D-010 Rev. 1	1997	29	5	34
NORSOK D-010 Rev. 2	1998-2003	175	36	211
NORSOK D-010 Rev. 3	2004-2012	291	28	319
NORSOK D-010 Rev. 4	2013-2016	207	12	219
	Sum	**1442**	**278**	**1720**

Fig. 23 and Table 7 shows the total number of wells with the status of P&A by different periods based on the regulations development. It shows that the largest number of wells with P&A status are in the period of 1981-1991.

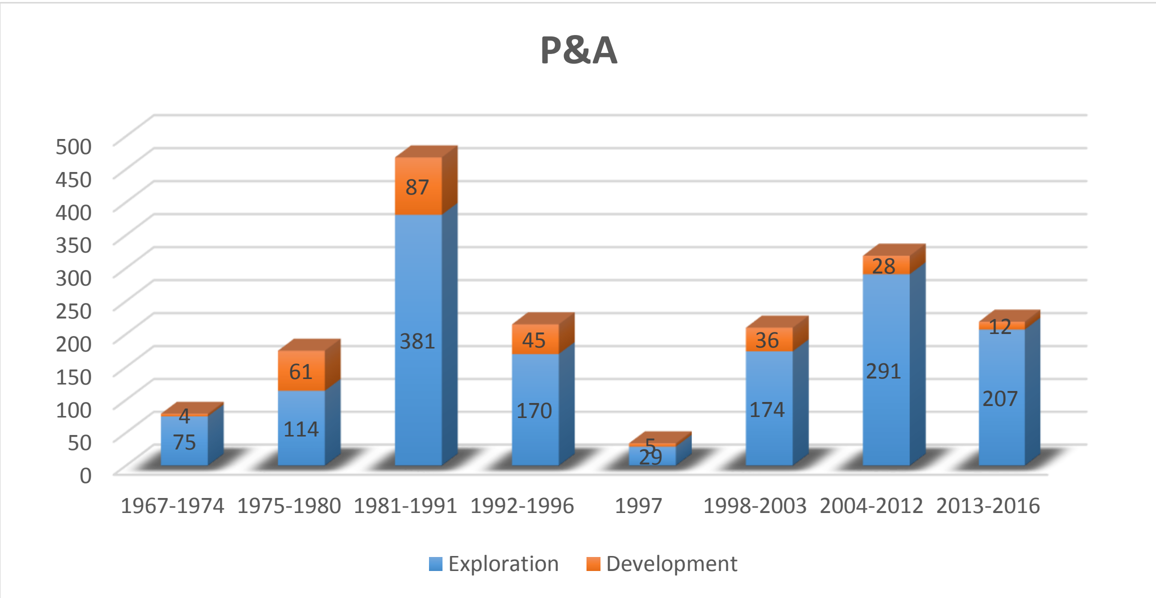

Figure 23: Plug and abandonment in relation to regulation validity periods.

Table 8: Number of wells with status Plugged per year by types

Regulations	Year	Exploration	Development	Total (Plugged)
Royal decree of 25th August 1967 relating to Safe Practice etc. in the Exploration and Drilling for Submarine Petroleum Resources	1967-1974	0	0	0
Regulations for drilling for petroleum in Norwegian internal waters.	1975-1980	0	29	29
Regulations for drilling etc. for petroleum in Norwegian internal waters	1981-1991	0	301	301
Regulations relating to drilling and well activities and geological data collection in the petroleum activities	1992-1996	0	271	271
NORSOK D-010 Rev. 1	1997	0	61	61
NORSOK D-010 Rev. 2	1998-2003	3	578	581
NORSOK D-010 Rev. 3	2004-2012	2	540	542
NORSOK D-010 Rev. 4	2013-2016	0	138	138
	sum	**5**	**1918**	**1923**

Fig. 24 and Table 8 shows the total number of wells with the status of Plugged by different periods based on the regulations development. It shows that the largest number of wells with P&A status are in the period of 1983-2003 followed by a period of 2004-2012.

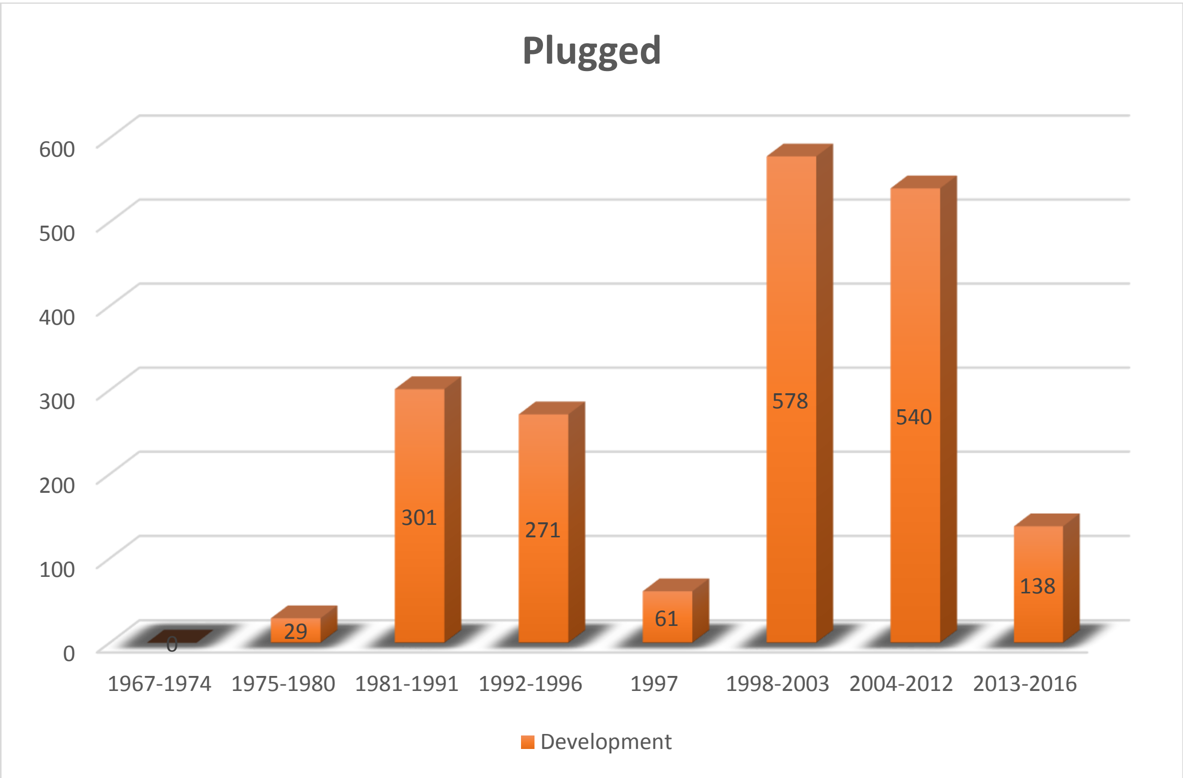

Figure 24: Plugged wells in relation to regulation validity periods.

7. Analysis

The responses from the oil and gas companies were very limited, we have received the following responses from the four companies who responded to our questionnaire; ConocoPhillips, Eni, Shell and Statoil.

The summary of the Statoil response:

NORSOK D-010 (rev. 3, 2004) set forth some new and 'trendsetting' requirements:

- 'Cross-sectional barrier'
- If the same cement job is a part of *both* the *Primary and the Secondary* barrier; the applicable cement job shall be logged by the use of an *azimuthal* logging tool. Comment: In principle, the PSA regulations specifies that the barriers shall be independent, the logging requirement is a mitigating measure.
- The barrier length requirements; 50 m (30 m logged)
- NORSOK D-010 (rev. 4, 2013) has 'softened up' some of the requirements in D-010 (rev. 3).

The changes in requirements, and not the least the importance of more cost-effective P&A solutions, has certainly triggered a boost in both the technology development and the willingness to use new methods to plug the wells.

The response from Eni Norge:

Eni Norge AS is an operator for two fields "Marulk and Goliat". In these two fields as per today, we have not perceived a need to plan for plugging any wells in the near future. When it comes to the exploration wells without finding any HC, we will comply with the current regulations.

The response from Norsk Shell AS:

Norsk Shell AS have plugged 3 production wells, 2 in autumn 2014 and 1 in 2015. The requirements in of NORSOK D-010 and Shell's own standard are used. The data background is therefore so thin and it is very difficult to conclude how the changes in D-010 over the years have affected well integrity/HSE/cost/operations etc. when the 3 wells were plugged according to the same standards. In terms of technology, we used new technology and LWIV as much as possible to reduce costs, as well as tried out several different methods for wellhead removal by boat.

Since then, our internal global manual has minor changes, it becomes less restrictive and more risk-based, and semantics focus on isolation rather than barrier.

Today's regulations combined with today's technology still make it impossible to make P&A on our remaining/producing wells completely without the use of rig, but it remains to be seen how both progress. E.g. we would like to cement through a tube from LWIV but the lack of CBL on csg / cmt + issue with control liner in cement. Another aspect is the Open hole to surface plug, which dictates the use of rig to pull production casing. In many cases, it may appear as a costly and weak barrier with poor verification.

The response from ConocoPhillips,

We have not seen any changes in regulations affecting our procedures, NORSOK D-010 will hopefully increase well integrity awareness. internal requirements in particular, the containment assurance requirements, addresses the reservoir management presently & in the future.

It is not regulatory changes, but technology changes like e.g. perf. Wash & cement that affects our P&A costs. it is our P&A campaigns that really results in cost improvements. It is the high costs associated with P&A that has driven the oil industry to look for new P&A technology. Several hundred MM NOK are invested searching new innovative P&A technologies.

Based on our contacts with the major companies in the field in order to assess their experience on what are the most important elements changed in the regulations related to P&A. There are no clear evidence or overview over what elements in the regulations have been changed and how these changes have been affecting operations in different companies.

7.1. Effects on technical integrity of wells

The effects of changes in regulations on the technical integrity have not been documented and it is hard to find as the permanently plugged wells have no monitoring activities in after the plugging.

The technical integrity of wells is classified based on the integrity of the barriers and risks related to each status. Table 9 shows the principles for each category, this classification is commonly used to define the status of the wells as it has been used the following figures.

Table 9: Well technical integrity status based on risk level and categories

Category	Principles
Red	One barrier failure and the other is degraded/not verified, or leak to surface.
Orange	One barrier failure and the other is intact, or a single failure may lead to leak to surface.
Yellow	One barrier degraded, the other is intact.
Green	Healthy well – no or minor issue.

Based on a survey carried out by PSA in 2014 (Gundersen, 2014), Fig. 25 shows the number of temporarily abandoned wells in 2014, the survey was covering both platform and subsea wells. From the total of 163 wells 8 of them had severe barrier failure (red category). In the same year, from a total of 119 subsea wells, no subsea wells were classified in the red category.

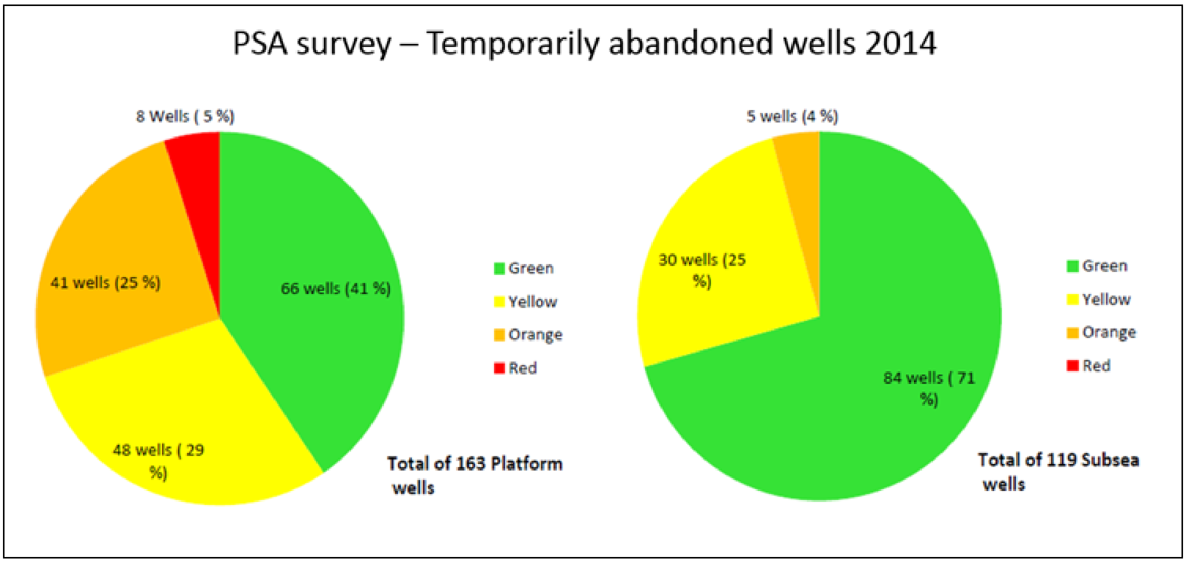

Figure 25: PSA survey - Temporary abandoned wells 2014. (Gundersen, 2014)

Based on a survey carried out by PSA in 2013 (Gundersen, 2016), Fig. 26 shows the number of temporarily abandoned wells in 2013, the survey was covering both platform and subsea wells. From the total of 163 wells 8 of them had severe barrier failure (red category). In the same year, from a total of subsea wells, no subsea wells were classified in the red category.

PSA survey – Temporarily abandoned wells 2013

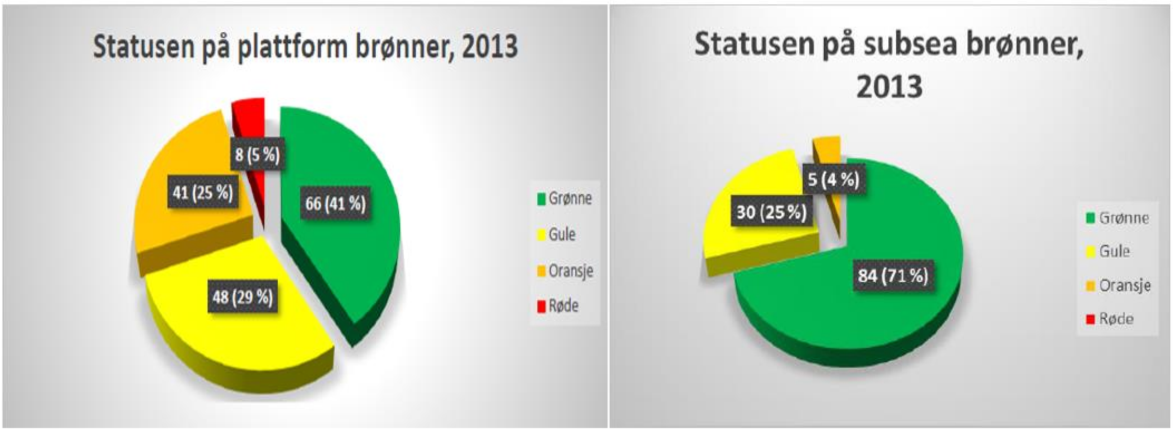

Figure 26: Temporarily abandoned wells status 2013. (Gundersen, 2016)

Based on the data from PSA in 2014, Fig. 27 shows the number of temporarily abandoned wells in 2014 for wells with and without monitoring. From the total of 282 wells 8 of them had severe barrier failure (red category) and 53% of the wells were categorised as a green category.

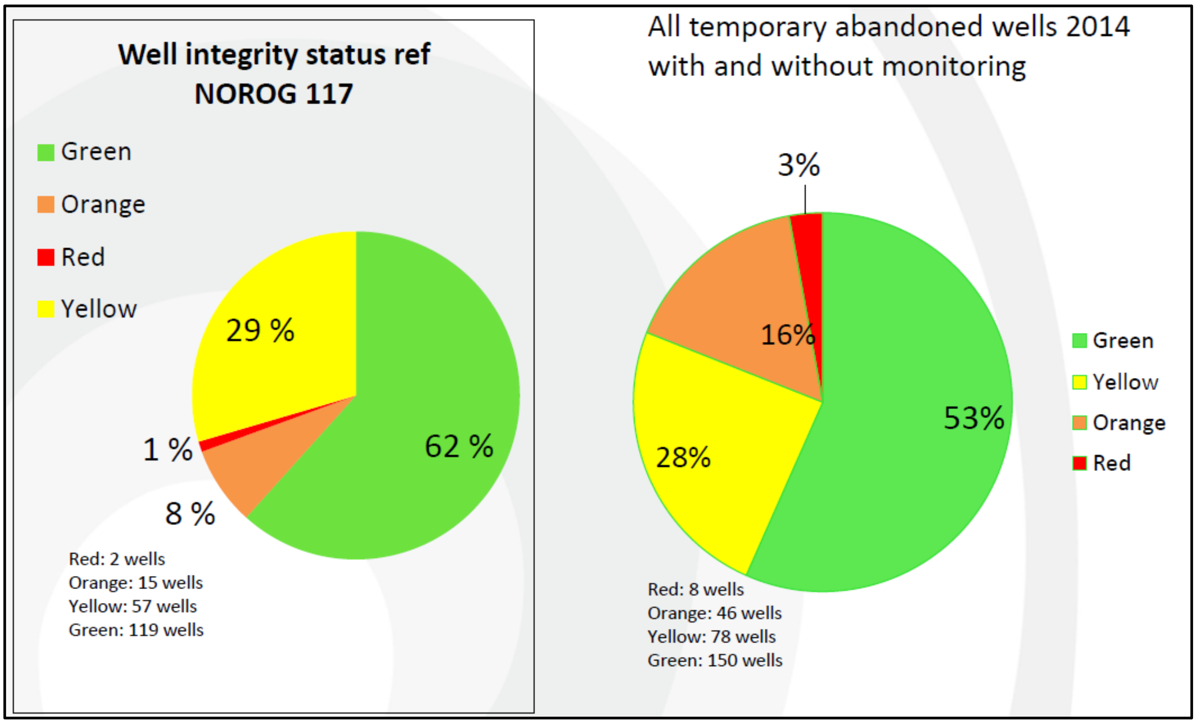

Figure 27: PSA Survey 2011/2014. (Gundersen, 2014)

The statistics from the PSA for 274 wells in 2016 showing the status of wells categorized based on their functions as shown in Fig. 28, 29 and 30.

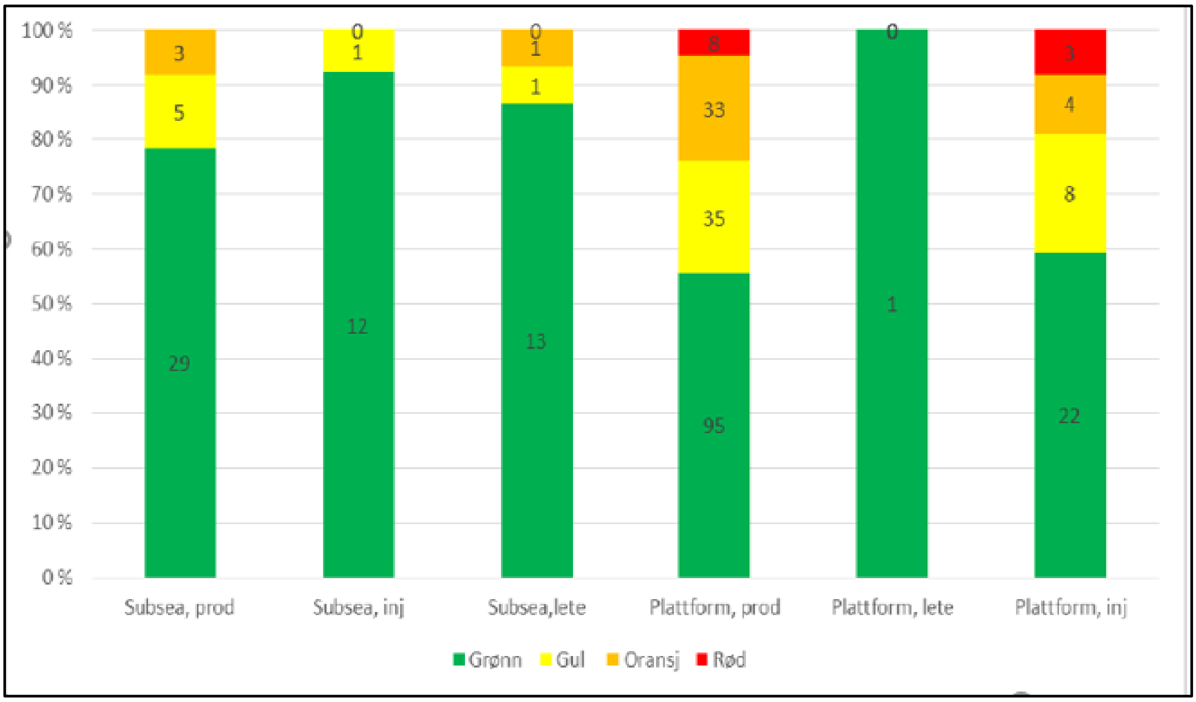

Figure 28: Status 2016 - all wells. (Gundersen, 2016)

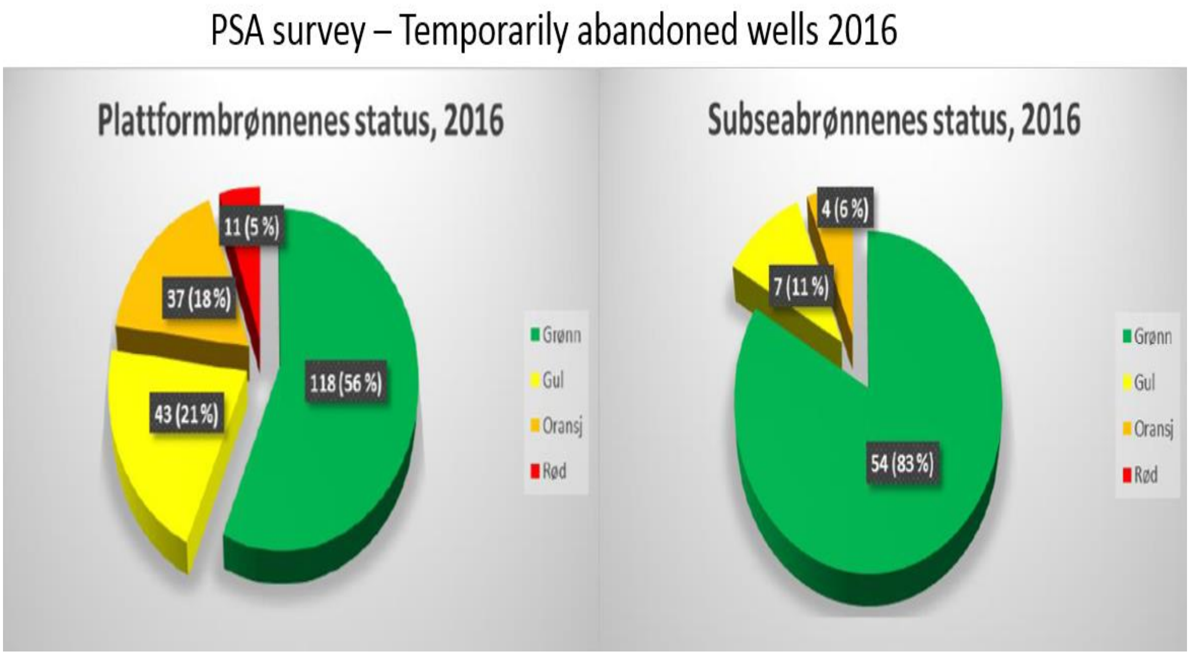

Figure 29: Status 2016 - all platform wells. (Gundersen, 2016)

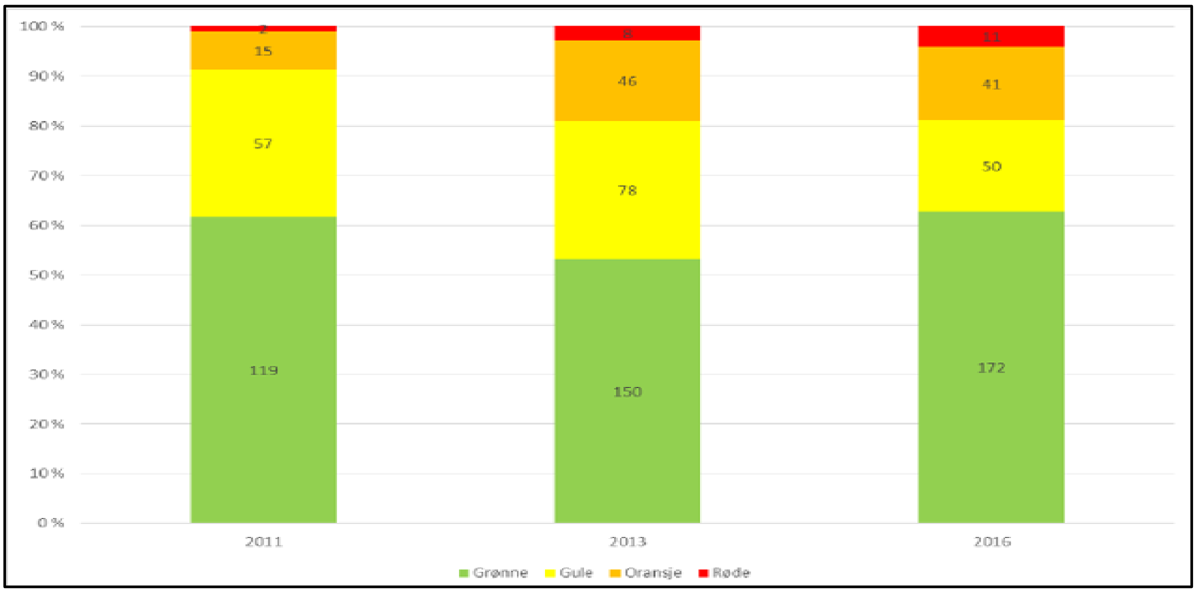

Figure 30: Comparison of all temporarily abandoned wells. (Gundersen, 2016)

7.2. Effects on the HSE issues

By looking at the operational aspect, the changes in P&A requirements might had a slightly negative effect on HSE, simply because more work must be executed in each P&A.

Fig. 31 shows the number of events per 100 wells, the overview is based on the information published from the RNNP report from the PSA. The figure showing a clear declining of the number of events/incidents in the last 6 years compared with the number of events in 2010.

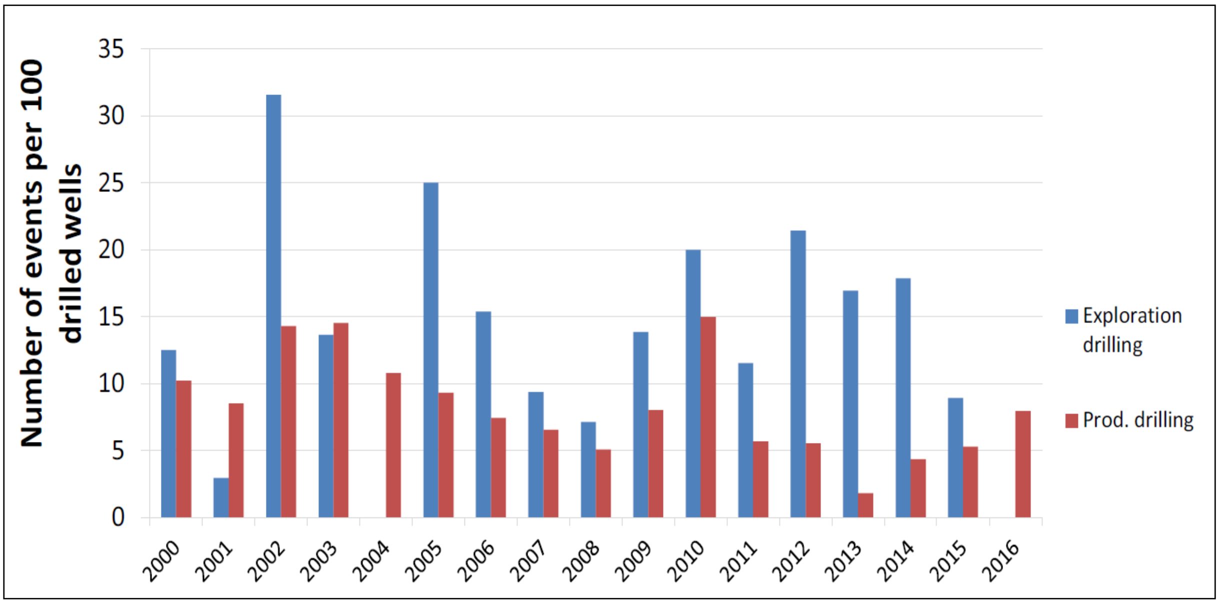

Figure 31: Well incidents per 100 wells drilled, for exploration and production drilling. (PSA, RNNP report 2017)

7.3. Effects on cost and investment

The cost of the plugging wells can be estimated by the location, complexity, period and several other elements. As it has been described in Fig. 32 from the presentation from DNV.GL, “the cost distribution in the upcoming plugging and abandonment jobs can be divided based on the phases of the well. It has been estimated that 22% is carried by owners, 46% with well P&A, and 18% for the removal” (McFarlane, 2016).

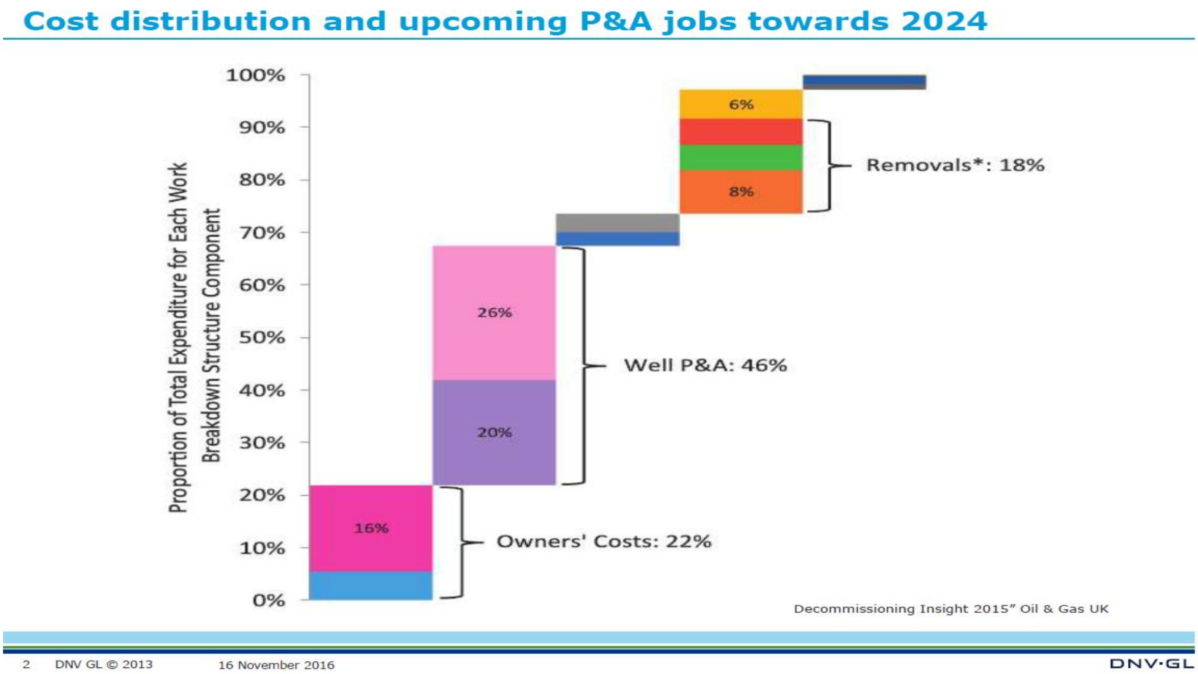

Figure 32: Cost distribution and upcoming P&A jobs towards 2024. (McFarlane, 2016)

Based on the Statoil response, there was a clear trend that the NORSOK D-010 (rev. 3, 2004) increased the Asset Retirement Obligation (ARO) budget. This effect **may** also have been a consequence of the high oil price around 2010. Since the increasing ARO/P&A cost was identified as a challenge; the P&A cost has come down by close to 50%, whereas the budgeted ARO/P&A cost has been reduced by approximately 25%.

This effect is both due to increased focus on the time/cost, challenging the requirements by taking a risk-based approach, slight modification of both industry standard and in-house requirements to open for cost effective solutions

- Up to 2012: P&A was not a big issue in Statoil; it was just budget figures in the ARO/P&A estimates. Very few jobs were executed.
- After 2012: Several P&A projects forced increased focus on P&A; It has experienced a close to 50% reduction in the P&A time/cost compared to our baseline based on the jobs performed in 2009 – 2013.
- We are certain that this can be improved even further (see Fig. 33).

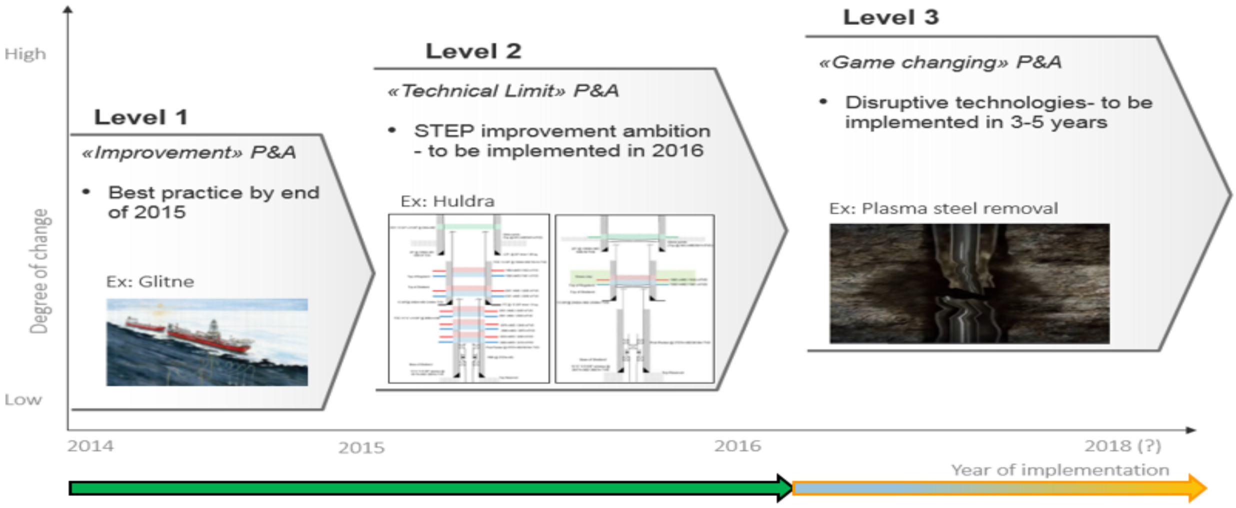

Figure 33: Cost reduction and improvements programs in P&A in Statoil.

7.4. Effects on the operations and effectiveness

The P&A operations have gone through major changes based on the development of the new technologies, and the companies' new capacities in the field. Companies in the last years had a high focus on the efficiency of their P&A operation and how to make it more effective.

The example from Statoil (Strøm, 2015) as shown in the Fig. 34 showing how they have been focusing on the effectiveness of their operations by going through all segments and finding what are the bottlenecks and time thieves and they have defined their major areas for P&A improvement.

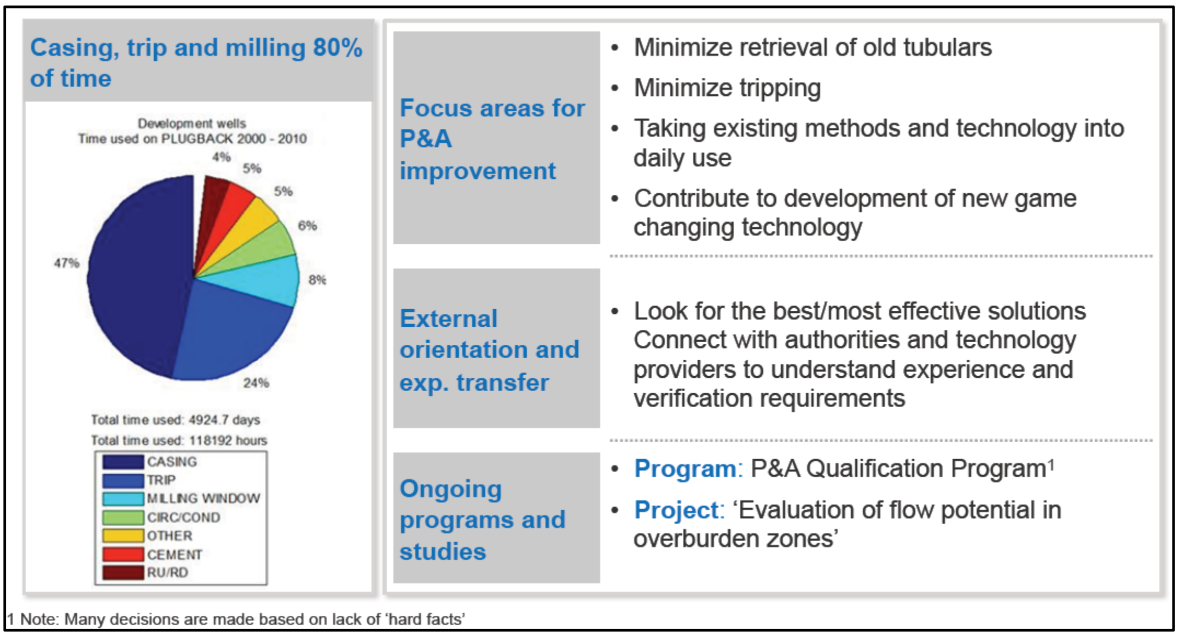

Figure 34: Improvement effort needs to address the major time thieves. (Strøm, 2015)

ConocoPhillips has another approach to defining their effectiveness and improvement strategies. As it is shown in Fig. 35, they have defined multiple parallel technology improvement strategies including the utilization and improving current P&A methods and look deeply into finding improvement through testing and utilizing new technologies.

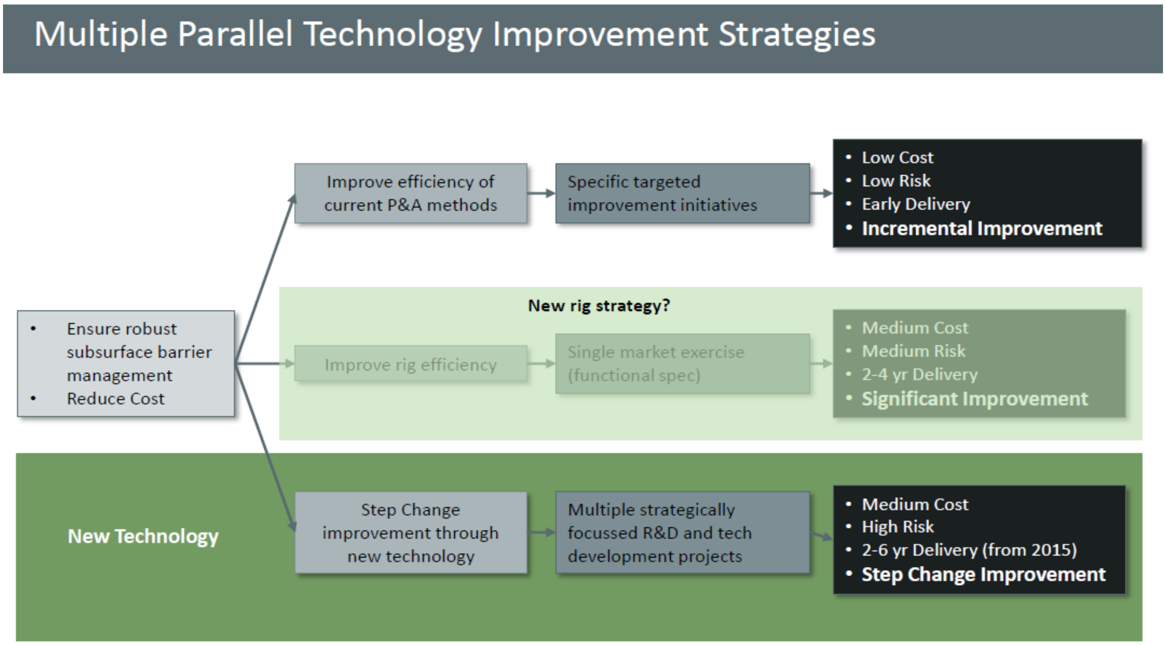

Figure 35: Multiple parallel technology improvement strategies. (Croucher, 2016)

The results from the ConocoPhilips experience as it is shown in Fig. 36, it is showing a clear improvement in P&A performances (days per well) up to 70% (Croucher, 2016).

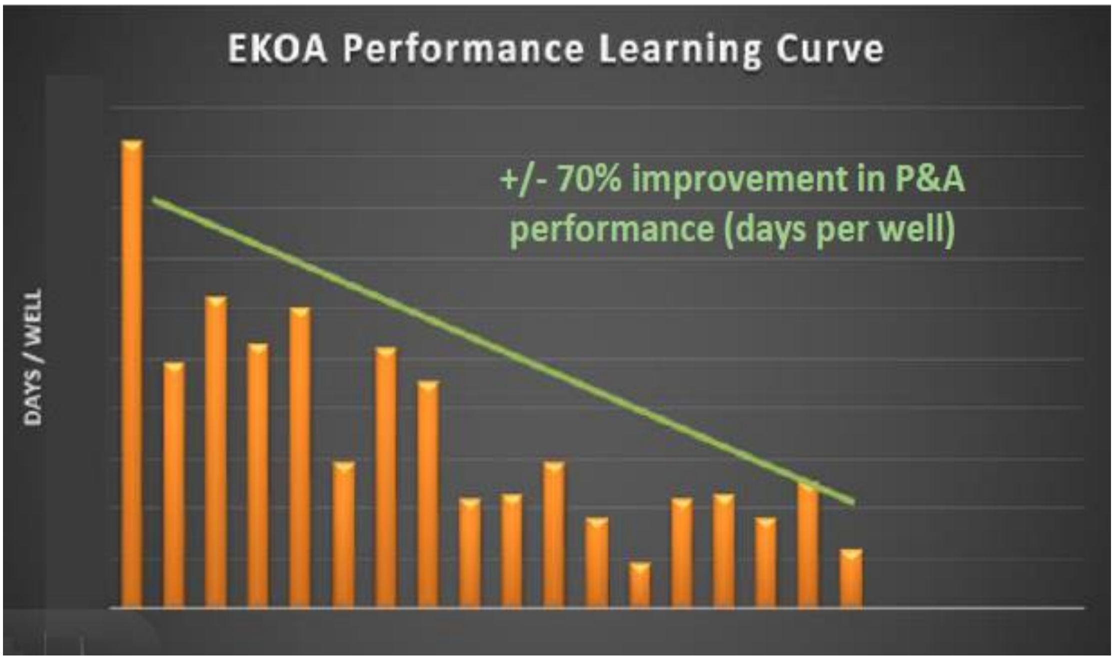

Figure 36: Performance learning curve. (Croucher, 2016)

7.5. Effects on resources used

There is no clear evidence how the changes of the regulations have been affecting the use of personnel or financial resources. In NCS it seems that the magnitude of the P&A activities will be increased in the forthcoming and as the last data from NPD stating, from the total of 6294 wells drilled since 1967, there have been only 1720 wells plugged and abandoned, there are still more than 4574 wells which needs to be plugged in the next 30 years.

A master thesis from the University of Stavanger; "by the end of 2013, a total of 5306 wells had been drilled on the NCS. 1469 of these were exploration and appraisal wells and were plugged relatively soon after. The remaining 3837 are production, injection and monitoring wells that have to be plugged eventually. Approximately 800 of these are already plugged and abandoned, leaving roughly 3000 wells for future P&A. Many of these wells are several decades old and their condition is poor, limiting the use of coiled tubing or wireline for efficient plugging methods" (Handal, 2014).

In the same study (Handal, 2014) it is stated that by "using extrapolation, one can presume that by the year 2050, a total of 7000 wells need to be plugged or are candidates for P&A. This estimate is based on trends developed over several years of operation on the NCS".

By using traditional technologies in the field, Statoil is "using 20-80 rig days per well and that is leading us to estimate the need for at least 15 rigs in operation for plugging wells in the next 40 years" (Straume, 2014).

7.6. Effects on the technology development

"The basic technologies associated with the plugging and abandoning of wells has not changed significantly since the 1970s" (NPC, 2011). These minor changes in the last years in terms of the technologies developed and utilised in the field, indicating that there still a long way to go with regard to the implementation of new technologies and further developing the existing technologies used in all phases of the P&A operations.

In the last two decades, the changes in requirements has impacted the cost and time it takes to P&A a well. The importance of more cost-effective P&A solutions has certainly triggered a boost in both the technology development and the willingness to use new methods to plug the wells.

The number of rig days to plug and abandon wells, have been reduced “up to 30 days on average with today’s technology (which is very optimistic)” (Handal, 2014). As it is shown in the Fig. 37 the number of days is varied depending on the technologies and methods used for plugging and abandonment.

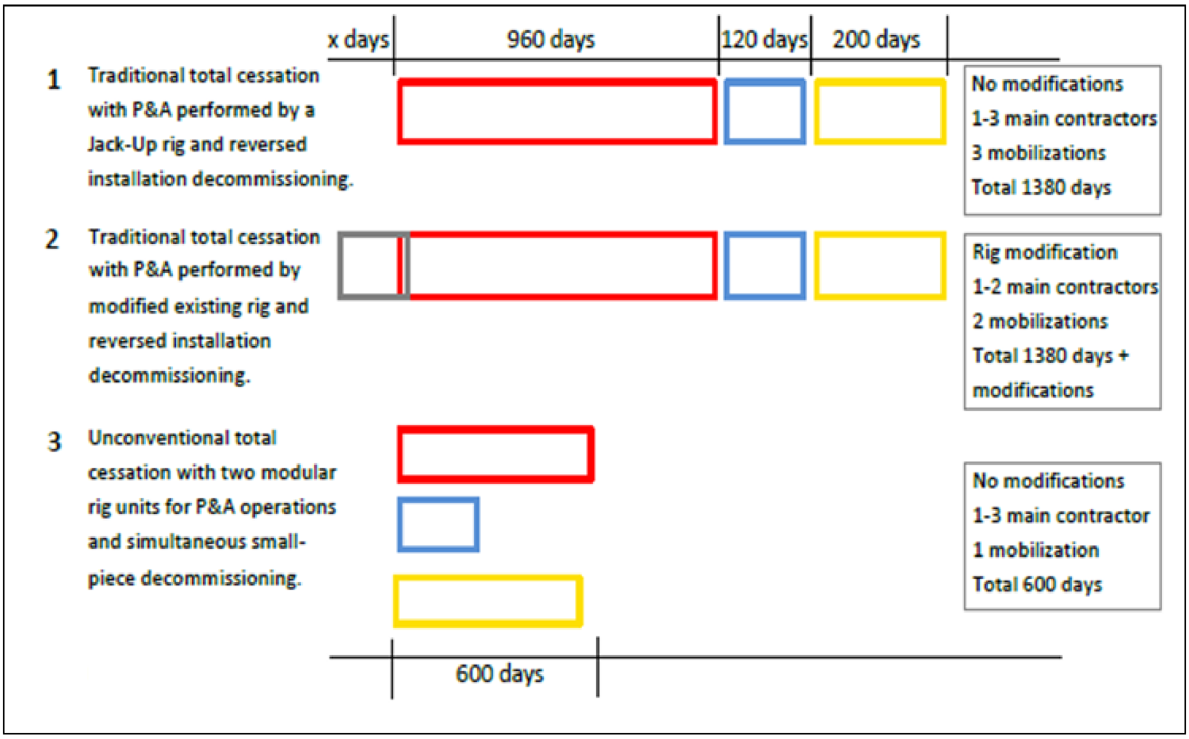

Figure 37: Plugging operations timeline. (Handal, 2014)

Several companies have developed own roadmap/plans for technology developments in P&A. Statoil has presented that road map as shown in Fig. 38 in different conferences and workshops highlighting the rigless P&A operations (Strøm, 2016).

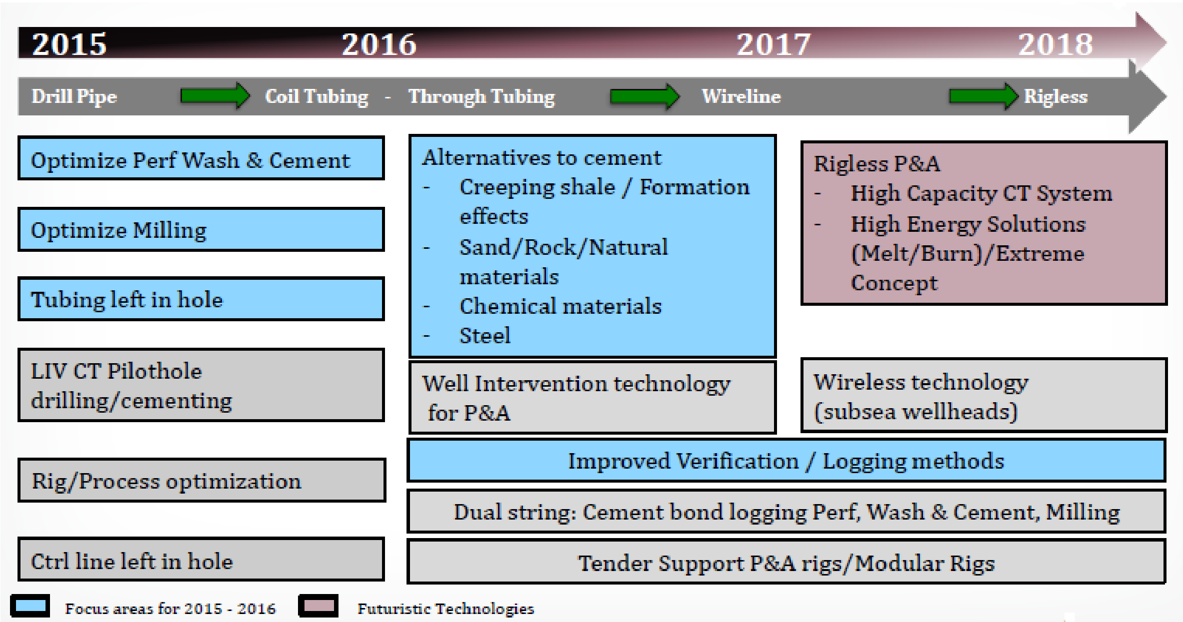

Figure 38: Roadmap for new P&A technologies. (Strøm, 2016)

8. Discussion

“The development of the regulations has gone parallel in different countries and authorities. The regulation of the oil and gas industry in the early days was driven by the need to protect the oil and gas resources and not the environment “(NPC, 2011). In Norway, the first regulation “Royal decree of 25th August 1967 relating to Safe Practice etc. in the Exploration and Drilling for Submarine Petroleum Resources” has contributed to establishing the cornerstone for the future development of the operations in the field of oil and gas and next versions of the regulations in 1975, 1981 and 1992 has been more focusing on the drilling and well activities including plugging and abandonment.

The drilling operations have been extended the need for special standard and have triggered the establishment of NORSOK D-010 standard in detail for the issues related to the well integrity and management. This standard as today is implemented in most of the companies and countries in the world. As it has been mentioned in our interview with major companies and their responsibilities, NORSOK D-010 is a basic for all technical and operational activities in these companies. The Macondo incident was a major background for the last version in 2013 with major support and contribution from the oil and gas industry.

In Norway, the regulations lead by authorities and Standard Norge started from 1967 and based on the experiences from other nations and operating companies. While in the US “the regulations in the field oil and gas had started in the 1890s, when Pennsylvania started regulating that wells should be plugged, the requirements were designed to protect the production zones from flooding by fresh water”. (Pennsylvania DEP, 2000; NPC, 2011). Later in 2010 in USA “the BSEE introduced Idle Iron regulations and guidelines for nonproducing wells in the GOM in a Notice to Lessees (known as an NTL), effective October 2010, which aims to provide oil and gas companies with some clarity about the required standards and outcomes expected as part of an abandonment philosophy” (Campbell, 2013).

Oil & Gas UK established the Guidelines for the Suspension and Abandonment of Wells, the document states the following: “All Distinct Permeable Zones penetrated by the well should be isolated, both from each other and from the surface or seabed by a minimum of one permanent barrier. Two permanent barriers from surface or seabed are required if a permeable zone is hydrocarbon bearing or over pressured and water bearing” (Campbell, 2013).

The information on the total number of the permanently plugged wells are varied, they are limited and varies from year to year. The majority of the data are based on the NPD database and according to the data presented in various conferences and seminars the number of wells in the period of 1966- 2014 were 5496 wells (23/10-14). 3978 of these were development wells and 1518 were exploration and appraisal wells (Straume, 2014).

Since 1967 and up to 20th April 2017 at the NPD database, 6294 wells were registered where 1720 of them has been plugged and abandoned (with a Status P&A), 278 of them are exploration wells whereas 1442 are development wells. This means that we have up 4574 wells as candidates for the future plugging.

"Permanent plugging of wells has been on the agenda at the Norwegian Oil and Gas over time, but the subject recently attracted greater attention" (Norsk Olje & Gass, 2015). By using the elementary calculations and estimation we can assume that this number will increase and it will be more than 7000 wells which need to be plugged and abandoned in until 2050. "This will take 210.000 rig-days to plug and abandon, assuming each well takes 30 days on average with today's technology" (Handal, 2014).

There is a great potential for cost saving due to technology development in the field of P&A and new wells in the 40 years. As described in Straume presentation in 2014, "the current cost and investment saving are around 637 billion NOK. It is as large as 57% of the Norwegian States budget in 2014" (Straume, 2014). "Minimizing costs, without sacrificing well integrity, is critical to operators, who make a significant investment with no financial return in the case of P&A operations" (Campbell, 2013).

During the period of implementation of NORSOK D-010 rev. 3, the time used for P&A operations has "increased significantly from 2003 to 2010. An increase from an average of 16 days per well to 35 days per well is a 120% escalation" (Handal, 2014), the detailing in regulation elements might be contributed to the increase of the number of days per well plugging and abandonment.

"According to the UK guidelines on qualification of materials for the suspension and abandonment of wells (Issue 1, July 2012) The barrier materials play an important role in contributing to the eternal perspective of the seal. For the purpose of PWA, the properties of the barrier materials should include the following:

- Long term integrity. The property of ¨durability¨ indicates that the service life should be approximately 3000 years (or one million days)
- Very low permeability. A good quality cement has typical permeability of 10 micro Darcy is deemed acceptable on the basis of historical experience" (Aguilar P., et al., 2016).

There are limited literature on the status of the integrity of the plugged and abandoned wells. “In recent shale-gas developments have rediscovered some P&A issues in the forms of older oil or gas wells which never were adequately plugged but which now pose possible cross contamination or leakage risks” (NPC, 2011).

“The lack of progress in P&A practices is attributable to the absence of a long-term vision, and in relation to corresponding research, that recognizes the benefits of P&A to oil and gas development projects” (NPC, 2011). “The use of rig for P&A-operations will lead to a delay drilling new wells, which again lead to delayed production and loss in net present value from the production in the field” (Myrseth et al., 2016).

As oil price increases, “many abandoned oil fields are re-entered with new technologies meant to produce oil that was not economical to produce in years past. With the new activity in the oilfield, any idle or unplugged wells not targeted for re-development must be plugged to prevent the escape of gas and oil from the reservoir” (NPC, 2011).

In 2015, the Norwegian Oil and Gas Association has stated that; “no potential exists for initiating additional plugging campaigns to increase the level activity in the industry” (Norsk Olje & Gass, 2015). As the result of oil price reduction in 2015, the rig market has changed, “the number of rigs available in the market has led to the reduction of costs across the whole industry and this might lead to increase the potential for increasing the P&A activities in the forthcoming years” (Norsk Olje & Gass, 2015).

“The plugging and abandonment of oil and gas wells have not changed significantly over the past 100 years. There has been an improvement in the quality of the materials and changes to the methods used to plug wells, but there has not been a specific change that has elevated the technology of plugging wells” (NPC, 2011). “In the future, the rigless technologies will play a significant role in reducing the cost of subsea well P&A and releasing semisubmersible rig time for drilling and completing new wells” (Moeinikia et al., 2014).

9. Conclusion

Based on the Norwegian Petroleum Directorates' reported data, "it has been estimated that there will be around 40-50 wells plugged each year in the coming years" (NPD, 2015). "The Operators on the NCS have informed Norwegian oil and gas that plans call for about 50-60 wells to be plugged over the next two years (2015-2016)" (Norsk Olje & Gass, 2015).

The majority of these wells will be plugged from fixed platforms. Data can be changed continuously as the number of newly drilled wells are changed. "The licence owners for these fields has the management responsibilities of these wells and has overviews over the number of wells in their own fields" (NPD, 2015).

Based on the number of wells that have been P&A since the starting of exploration in Norway combined with the well integrity data from temporarily P&A wells. There is little evidence on how the changes in regulations have had the effect on the P&A operations and activities in the NCS.

The major changes can be seen in the field of investments and costs per wells. NORSOK D-010 has become a recognised standard not only for Norway but for the whole Drilling industry across the globe.

Rev. 3 and 4 of the NORSOK D-010 has had a visible effect on the length and content of the operations as new elements were introduced as PWC and section millings major. These changes have led to extending time and duration of P&A operations and associated utilisation of resources and costs.

For conducting this study, I have contacted major operating companies in Norway, but unfortunately I have received limited feedback.

The only data accessible is based on the NPD database which is of poor quality and limited to what the companies are reporting. It is hard to find if the plugged status is permanently or temporarily plugged status for wells.

Based on my correspondence with PSA, they have stated that; the incident registration database of the PSA has limited information on the P&A, no attributes in the database are used for P&A incidents.

The integrity of the plugged and abandoned wells remains unknown as there are no requirements for monitoring after finalising the plugging and the abandonment of the fields. These might have a future impact on the integrity of the plugged wells.

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Appendix A.1

Questionnaire:

The purpose of this questionnaire is to find the main changes in the P&A requirements on the NCS and its effects on permanently plugged wells.

Please answer the following questions: -

Q1: Based on your experience what are the most important elements changed in the regulations in P&A?

Q2: How have the changes in P&A requirements affected the Technical integrity of wells?

Q3: How have the changes in P&A requirements affected the HSE issues?

Q4: How have the changes in P&A requirements affected your company investment and the cost of plugging wells?

Q5: How have the changes in P&A requirements affected the operations and the effectiveness?

Q6: How have the changes in P&A requirements affected the resources utilization in permanently plugged wells?

Q7: How have the changes in P&A requirements affected the technology development and implementation of new ideas and methods?

Please send the response to Nina Larsen email

Appendix A.2

Royal Decree of 25th August, 1967 relating to Safe Practice etc. in Exploration and Drilling for Submarine Petroleum Resources.

Chapter V

Abandonment of wells

Section 64.

A well cannot be abandoned unless the Ministry has been notified at least 24 hours in advance. The licensee shall explain in the notification the reasons for abandoning the well. He shall furthermore submit a plan for how the well will be plugged, secured and abandoned. The Ministry may stipulate a time limit within which each installation in or above the well shall be removed.

Section 65.

When a well is abandoned, casing strings and cement in the well must not be removed or destroyed — except as provided in Section 67 — without the written consent of the Ministry.

Section 66.

An abandoned well shall be plugged — in accordance with good oilfield practice — with top cement plugs and with additional cement plugs in such a number, of such length and with such spacing between the individual plugs as is required in order to maintain complete control of the well and prevent the escape of fluids from the well or penetration of salt water or other alien matter into the well.

The well, including the interval between the cement plugs, shall be filled with drilling fluid or other fluid of sufficient density and with such other properties to safely withstand, together with the plugs, any pressure which may develop within the well.

Section 67.

When a well is abandoned, parts of casing strings and other installations protruding from the seabed must — except as provided in Section 64 to 66 —be removed to such a depth that no obstruction remains which may cause danger or impediment to fishing or shipping. Before final abandonment of the well, the licensee must make sure that on the seabed, and on the surface of, or in the vicinity of the drilling location, no obstructions of any kind remain, as a result of his operations, which may cause damage or impediment to fishing, shipping or other activities.

Appendix A.3

Regulations for drilling for petroleum in Norwegian internal waters, in Norwegian territorial waters and on the Continental Shelf which is under Norwegian sovereignty, issued by the Norwegian Petroleum Directorate 29th August 1975.

Section 25 Abandonment of Wells

2.1. In a part of a well where casing has not been installed and where fluid or gas have been found in permeable zones, cement plugs shall be placed to isolate fluids in the strata in which they are found and prevent them from escaping into other strata. In the zone concerned the cement plug shall be placed in such a way that the upper and lower part of the plug is located at a minimum of 30 m (100 feet) above and below the zone.

2.2. Where there is open hole below the deepest casing, the cement plug shall be placed in such a manner that it extends a minimum of 30 m above and below the casing shoe. If the condition of the formation makes cementing difficult a mechanical plug can be positioned in the lower part of the casing, but not more than 50 m above the shoe. Above the said mechanical plug there shall be placed a cement plug of at least 15 m.

2.3 Perforations shall be isolated by means of a mechanical plug and is to be squeeze cemented or a cement plugs shall be placed opposite all open perforations extending a minimum of 30 m above and below the perforated interval or own to a casing plug, whichever is less.

2.4 If a liner has been used, a cement plug shall be placed in such a manner that the plug extends 30 m above and below the point of suspension.

2.5 There shall be no communication from open formation in the drilled hole below to the ocean floor via any annular space between two sets of casing string. In the cases where the cement is not brought up at least 100 m (300 feet) into previously set string of casing, the last string of casing shall be perforated at the point of the previously set string of casing's shoe and squeeze cemented with a volume at least equal to a cement column of 100 m (300 feet) in the annular space.

2.6. A cement plug of at least 30 m shall be placed in the smallest string of casing which extends to the ocean floor. The plug shall be placed at the level of the surface casing shoe.

2.7. A cement plug of at least 150 feet, with the top of the plug 150 feet or less below the ocean floor, shall be placed in the smallest string of casing which extends to the surface. Her har vi noen tall som ikke stemmer med den norske versjonen som er I same paragraph og same år.

2.7. En sementplugg av minimum 100 m (300 fot) lengde skal plasseres slik at toppen av pluggen kommer 50 m (150 fot) eller mindre fra sjøbunnen. Den nedre del av pluggen skal være sementert inn i det indre foringsrør.

2.8 The interval between the cement plugs shall be filled with drilling mud or other fluid of sufficient density and with such other properties to safely withstand, together with the plugs, any pressure which may develop within the well.

2.9 When a well is abandoned, parts of casing strings and other installations extending above the ocean floor must -; except as provided in paragraph 1.4 – be removed to such a depth or at least 5 m (15 feet) below the ocean floor, so that no obstruction remains which may cause danger or impediment to fishing or shipping.

1.4. When a well is abandoned, casing strings and cement in the well must not be removed or destroyed except as provided in paragraph 2.9 – without the written consent of the Norwegian Petroleum Directorate.

2.9 Når et borehull oppgis, skal – med de innskrenkninger som følger av pkt. 1.2 – den del av rørveggen og andre installasjoner som stikker opp» fra havbunnen, fjernes til en slik dybde, dog minst 5 m.

1.2. Plugging and permanent abandonment shall be conducted immediately after the well is drilled and possibly tested. This work shall normally take place from the drilling platform that drilled the actual well.

Appendix A.4

Regulations relating to drilling and well activities and geological data collection in the petroleum activities. Regulations for drilling etc. for petroleum in Norwegian internal waters. in Norwegian territorial waters and on the Continental Shelf which is under Norwegian sovereignty. Issued by the Norwegian Petroleum Directorate 23 September 1981.

ABANDONMENT OF PRODUCTION WELLS

Permanent Abandonment of Borehole or Production Well

9.3.2 In parts of the borehole where casing has not been installed and here permeable zones containing liquid or gas have been found. Cement plugs shall be placed in such a way as to prevent liquid or gas from seeping into other zones. For each individual zone the cement plug hall be positioned such that it's upper and lower ends are located at least 50 m above and below the zone respectively. The top of each cement plug shall be located and verified by mechanical loading.

9.3.3 Where there is open hole below the deepest casing, the cement plug shall be placed in such a manner that it extends a minimum of 50 m above and below the casing shoe. If the condition of the formation makes cementing difficult a mechanical plug can be positioned in the lower part of the casing, but not more than 50 m above the shoe. Above the said mechanical plug there shall be placed a cement plug of at least 20 m.

9.3.4 Perforated zones shall be isolated by means of a mechanical plug and shall be squeeze cemented. If this is not possible. A cement plug shall be placed in such a way that the upper and lower ends of the plug are located at least 50 m above and below the perforated zone respectively. Or down to the nearest plug if the distance is less than 50 m.

9.3.5 If a liner has been used, a cement plug shall be placed in such a manner that the plug extends 50m above and below the point of suspension.

9.3.6 There shall be no communication from open formation in the borehole to the sea-bed via any annular space between two sets of casing strings. In cases where the cement is not brought up at least 100 m into previously set casing, the last casing
string shall be perforated 100 m
above the shoe of the previously set casing string, and be squeeze cemented with a volume at least equal to a cement column of 100 m in the annular space.

9.3.7 A cement plug at least 200 m long, with the top of the plug 50 m or less below the sea-bed, shall be located in the smallest string of casing which extends to the surface.

9.3.8 The borehole, including the spaces between the cement plugs, shall be filled with drilling fluid or other fluid of sufficient density and with such other properties as to enable it to withstand, together with the plugs, any pressure which may develop in the borehole.

Appendix A.4

Regulations relating to drilling and well activities and geological data collection in the petroleum activities. Stipulated by the Norwegian Petroleum Directorate 7 February 1992.

SECTION 51 PLUGGING

Permanent plugging

When a subsea well is permanently plugged, all equipment extending up from the sea bed shall be removed to a sufficient depth below the sea bed.

Methods for cutting of wellheads and associated equipment shall be evaluated in relation to consequences for the integrity of the well and external environmental loads. Explosives are not permitted used for cutting of the casing string to remove the wellhead.

The operator shall immediately carry out the necessary inspections to ensure that no obstructions of any kind capable of damaging or impeding fishing, shipping or other activities, remain at the drilling location on the sea bed.

Guidelines on cementing in the petroleum activities to the Norwegian Petroleum Directorate's Regulations concerning drilling and well activities and geological data collection, issued by the Norwegian Petroleum Directorate 7 February 1992.

8 PLUGGING

8.1 Permanent plugging/abandonment the main purpose of permanent plugging is to prevent on a permanent basis gas and formation fluid from flowing between the various zones in the well that contain hydrocarbons, and from such zones and up to the surface. Already at the planning stage of the well, the need to be able to comply with the requirements relating to plugging should be taken into consideration. The necessary logs of cement quality and lithology together with the assessments made in connection with the primary cementing operations will constitute the basis for the installation and number of plugs/packers when the plugging program is prepared.

The requirements set out below are in accordance with current practice. The requirements relating to permanent plugging/abandonment are to be complied with on the outside of the casings as well as on the inside.

Perforation/cutting of casings and squeeze cementing of the annulus is to be carried out in such a way as to comply with the requirements relating to primary cementing operations.

Inside the casing strings (intermediate casing, production casing and liners), potential flow sources shall be located and influx prevented by means of at least two barriers. This will entail securing all annular spaces of production casing, all casing cuts, the shoe of the deepest string

of casing and all perforations. The barriers may be combinations of the primary cementing, squeeze cementing or cement plug/mechanical packer (bridge plug). At least one of the barriers shall consist of cement.
When a well is permanently abandoned, all perforated zones shall be isolated by means of a mechanical plug, and shall be squeeze cemented.

The minimum height of cement plugs during plugging shall be 100 meters. Cement plugs shall extend to at least 50 m from the top of the permeable zone and upwards or 50 m from the potential flow point and upwards.

Requirements relating to minimum height and extent will not be applicable for plugging in connection with conductor casing and surface casing having been cemented back to the sea bed.

Cement plugs and packers should be located as close to the potential flow sources as possible. A 200-m cement plug is to be placed at the top of the well, so that the top of the plug is not more than 50 m below the sea bed.

The barrier which is placed in the transition between open hole and casing shall be located, subjected to a mechanical load of at least 10 tons and be pressure tested to 70 bar above measured formation strength of the last set casing string.

When cut intermediate casing, production casing and liners are plugged, it shall be verified by pressure testing to 70 bar above the formation strength that potential flow paths are isolated and sealed.
In connection with plans for permanent plugging, a detailed program shall be prepared indicating:

a) purpose/objective of the plugging;
b) design criteria;
c) design parameters;
d) step by step procedure;
e) sketch of the well, indicating location of plugs/packers, top of cement in the annulus, cutting depth of casing and other significant details.

The program shall be forwarded to the Norwegian Petroleum Directorate prior to plugging/abandonment of the
well, cf. Section 11 of the regulations.

Appendix B.1

NORSOK D-010 Rev. 1, September 1997

DRILLING & WELL OPERATIONS

5.4.9 Cement Plug barrier

A cement plug being part of an abandonment program shall extend a sufficient length above the highest leak passage (i.e. casing shoe, liner hanger, perforation etc.):

a) Open hole; 50 m (min. total 100 m cement plug)

b) Cased hole; 100 m alternatively mechanical bridge plug with 20 m top cement if run as a retainer

c) A top plug of 200 m is to be placed at the top of the well, so that the top of the plug is not more than 50 m below the sea bed.

Isolation is verified by pressure test to 70 bar above measured formation. Also 10 tons weight test to be performed for plugs against open hole/leak passage.

Appendix B.2

NORSOK D-010 Rev.2, December 1998

DRILLING & WELL OPERATIONS

5.1.2 Plugging & Abandonment

5.1.2.1 General

A plugging and abandonment program shall be prepared and submitted to the NPD at least one week prior to the commencement of activities.
The well shall be secured by means of two barriers in line with the requirements listed under 'Barriers' above. The abandonment shall entail the securing of all annular spaces between casings, all casing cuts, the shoe of the deepest set casing and all perforations.

The barriers may be a combination of any two (2) of the following, with at least one (1) barrier consisting of cement.

d) The primary cementation.
e) Squeeze cementation.
f) Cement plugs.
g) Mechanical packer.
h) Mechanical bridge plug.
i) Thermo-set resin.

All perforations shall be isolated by means of a squeeze cementation or thermo-set resin, and a mechanical barrier.

In general, barriers shall be pressure tested to 70 bar above expected formation strength below shoe of the deepest casing string. However, the test pressure shall not exceed previous casing test pressure.

Cement plugs placed in the transition zone between open hole and casing shall be subjected to a mechanical load of at least 10 tons.

5.1.2.2 Permanent plugging and abandonment

The well shall be plugged according to a separate plug and abandonment programme in such a way that the general requirements in section **5.1.2** are fulfilled.

5.1.2.3 Plugging of open hole

Cement plugs with minimum length of 100 m shall be set to isolate permeable zones in open hole.
Cement plugs shall extend minimum 50 m from the top of the permeable zone and upwards, or 50 m from the potential flow point and upwards.

A barrier shall be placed in the transition zone between open hole and casing. The barrier can be either a mechanical packer or a cement plug, extending for a minimum of 50 m above and below the casing shoe.

5.1.2.4 Plugging of perforations

Prior to installing a squeeze retainer an injection rate through perforations shall be established. If injection is obtained, all perforated zones shall be isolated with a mechanical plug and squeeze cemented.

If the injection rate cannot be obtained, a cement plug shall be set across perforations extending a minimum of 100 m above the top perforations. If the distance between the test intervals is less than 100 m thus making a 100 m cement plug impossible, a mechanical packer should be set as close to the top of the perforations as possible.

Minimum of 10m cement shall be left on top of the squeeze retainer.

5.1.2.5 Plugging of liner laps

A cement plug shall stretch for a minimum of 50 m above and below the liner top.

5.1.2.6 Cut and pull of casings

Each casing shall be cut at sufficient depth to fulfil all barrier requirements. Cutting the casing, perforating casings and retrieving seal assemblies shall be performed under complete pressure control to relieve overpressures in annulus between casings.

A float valve shall be used in the BHA during cutting operation.

To enable circulation when pulling on cut casings, a spear with pack-off or casing-landing string shall be used.

Explosives are not permitted used for cutting the casing string to remove the wellhead. Only in exceptional cases and several unsuccessful attempts with mechanical cutters, can the use of explosives be accepted. The use of explosives shall in such cases be handled as a deviation from the NPD regulations.

The wellhead and the following casings shall be removed so that the top cut is minimum 5 m below seabed.

5.1.2.7 Plugging above cut casings

Potential flow sources behind the casing strings shall be located and plugged with a minimum of two barriers to secure all annular spaces and casing cuts. At least one of these shall be a cement barrier.

The minimum height of a cement plug shall be 100 m. Cement plugs shall extend minimum 50 m from the top of a permeable zone and upwards, or 50 m from a potential flow point and upwards.

Requirements related to minimum height and length are not applicable to the plugging of conductor casing and/or surface casings cemented to the seabed.

5.1.2.8 Surface plug

The surface cement plug shall be minimum 200 m in length and the top of the cement shall run no deeper than 50 m below the seabed.

Appendix B.3

NORSOK D-010 Rev.3, August 2004

Well integrity in drilling and well operations

9.3.8 Permanent abandonment

9.3.8.1 General

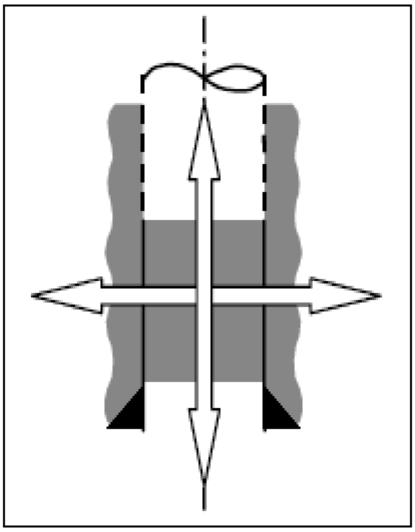
Permanently plugged wells shall be abandoned with an eternal perspective, i.e. for the purpose of evaluating the effect on the well barriers installed after any foreseeable chemical and geological process has taken place.

There shall be at least one well barrier between surface and a potential source of inflow, unless it is a reservoir (contains hydrocarbons and/ or has a flow potential) where two well barriers are required.

When plugging a reservoir, due attention to the possibilities to access this section of the well (in case of collapse, etc) and successfully install a specific WBE should be paid.

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.

9.3.8.2 Permanent well barriers



Permanent well barriers shall extend across the full cross section of the well, include all annuli and seal both vertically and horizontally (see illustration). Hence, a WBE set inside a casing, as part of a permanent well barrier, shall be located in a depth interval where there is a WBE with verified quality in all annuli.

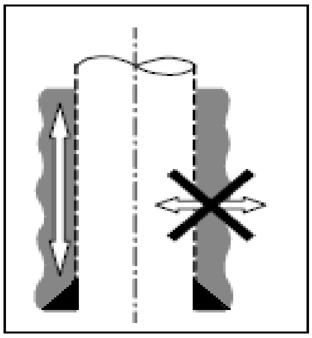
A permanent well barrier should have the following properties:

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.

Steel tubular is not an acceptable permanent WBE unless it is supported by cement, or a plugging material with similar functional properties as listed above, (inside and outside).

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

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 will not qualify as a WBE across the well (see illustration).



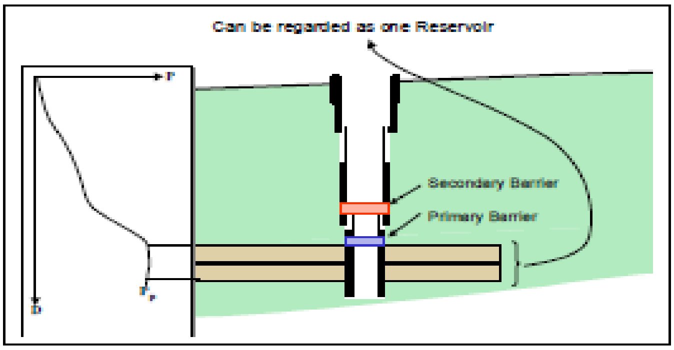
Open hole cement plugs can be used as a well barrier between reservoirs. It should, as far as practicably possible, also be used as a primary well barrier, see Table 24.

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

Removal of downhole equipment is not required as long as the integrity of the well barriers is achieved.

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.

When well completion tubulars are left in hole and permanent plugs are installed through and around 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.



9.3.8.3 Special requirements

Multiple reservoir zones/ perforations located 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 (see illustration).

9.4 Well barrier elements acceptance criteria

9.4.1 General

Subclause 9.8 lists the WBEs that constitute the primary and secondary barriers for situations that are illustrated.

9.4.2 Additional well barrier elements (WBEs) acceptance criteria

The following table describes features, requirements and guidelines which are additional to what is described in Clause 15.

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.

No.	Element name	Additional features, requirements and guidelines
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.

9.4.3 Common well barrier elements (WBEs)

A risk analysis shall be performed and risk reducing measures applied to reduce the risk as low as reasonable practicable, see 4.2.3.3.

The following table describes risk reducing measures that can be applied when a WBE is an element in the primary and secondary well barrier:

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.

9.5 Well control action procedures and drills

9.5.1 Well control action procedures

The following table describes incident scenarios for which well control action procedures should be available (if applicable) to deal with the incidents should they occur. This list is not comprehensive and additional scenarios may be applied based on the actual planned activity, see 4.2.7.

Item	Description	Comments
1.	Cutting of casing.	Trapped gas pressure in casing annulus.
2.	(SSW) Pulling casing hanger seal assembly.	Trapped gas pressure in casing annulus.
3.	Re-entry of suspended or temporary abandoned wells.	Account for trapped pressure under plugs due to possible failure of suspension plugs.

9.5.2 Well control action drills

The following well control action drills should be performed:

Item	Description	Comments
1.	Pressure build-up, or lost circulation in connection with a cutting casing operation.	To verify crew response in applying correct well control practices.
2.	Loss of well barrier whilst performing inflow test.	

9.6 Suspension, plugging and abandonment design

9.6.1 Design basis, premises and assumptions

Depths and size of permeable formations with a flow potential in any wellbore shall be known.

All elements of the well barrier shall withstand the pressure differential across the well barrier at time of installation and as long as the well barrier will be in use, see 9.3.3.

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

a) 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.
b) 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.
c) Logs, data and information from primary cementing operations in the well.
d) Estimated formation fracture gradient.
e) Specific well conditions such as scale build up, casing wear, collapsed casing, fill, or similar issues.

The design of abandonment well barriers consisting of cement should account for uncertainties 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.

9.6.2 Load cases

Functional and environmental loads shall be combined in the most unfavourable way.

For permanently abandoned wells, the specific gravity of well fluid accounted for in the design shall maximum be equal to a seawater gradient.

The following load cases should be applied for the abandonment design:

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.

9.6.3 Minimum design factors

The design factors shall be as described in 5.6.4 and 7.6.4.

9.7 Other topics

9.7.1 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 be assessed.

9.7.2 Removing equipment above 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.

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, sea bed scouring, sea current erosion, etc.. The cutting depth should be 5 m below seabed.

No other obstructions related to the drilling and well activities shall be left behind on the sea floor.

Appendix B.4

NORSOK D-010 Rev. 4, Juni 2013

Well integrity in drilling and well operations

9.6 Permanent abandonment

9.6.1 General

This section covers requirements and guidelines pertaining to well integrity during permanent abandonment. Permanent abandonment is defined as a well status, where the well is abandoned and will not be used or re-entered again.

9.6.2 Well barrier acceptance criteria

Permanently abandoned wells shall be plugged with an eternal perspective taking into account the effects of any foreseeable chemical and geological processes. The eternal perspective with regards to re-charge of formation pressure shall be verified and documented.

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The following individual or combined well barriers/isolations shall be a result of well plugging activities:

Table 24 – Well barrier depth position

Name	Function	Depth position
Primary well barrier	To isolate a source of inflow, formation with normal pressure or over-pressured/ impermeable formation from surface/seabed.	The base of the well barriers shall be positioned at a depth were formation integrity is higher than potential pressure below, see 4.2.3.6.7 Testing of formation.
Secondary well barrier	Back-up to the primary well barrier, against a source of inflow	As above
Crossflow well barrier	To prevent flow between formations (where crossflow is not acceptable). May also function as primary well barrier for the reservoir below.	As above
Open hole to surface well barrier	To permanently isolate flow conduits from exposed formation(s) to surface after casing(s) are cut and retrieved and contain environmentally harmful fluids. The exposed formation can be over-pressured with no source of inflow. No hydrocarbons present.	No depth requirement with respect to formation integrity

The overburden formation including shallow sources of inflow shall be assessed with regards to abandonment requirements.

Multiple reservoir zones/perforations located within the same pressure regime can be regarded as one reservoir for which a primary and secondary well barrier shall be installed (see figure 9.6.2.1).

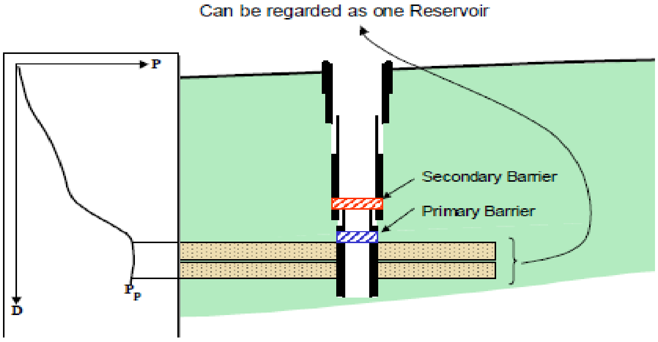

Figure 9.6.2.1 – Multiple reservoirs