

# Plug & abandonment of offshore wells: Ensuring long-term well integrity and cost-efficiency



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## ARTICLE INFO

### Keywords:

Plug and abandonment  
Well integrity  
Cost-efficiency  
Barriers  
Subsea

## ABSTRACT

There is an upcoming "P&A wave" of wells that need to be permanently plugged and abandoned, especially in mature, offshore areas such as the North Sea and Gulf of Mexico. It is important to ensure that plugged wells do not leak after abandonment, as there could be several potential leak paths such as microannuli in plugged wells. To ensure well integrity after abandonment, permanent well barriers must extend across the full cross section of the well. That includes establishing barriers in all annuli, which could however be quite time-consuming and thus costly.

This paper is a review of challenges and technologies for P&A of offshore wells, with an emphasis on cost-effective solutions while establishing permanent well barriers. An overview of cement and other plugging materials is given, as well as a discussion of different types of potential leak paths and failure mechanisms in permanently plugged and abandoned wells. Moreover, recent technology developments such as utilizing shale as barrier for P&A are described. A discussion on the special considerations related to P&A of subsea wells is also included.

## 1. Introduction

When a well reaches the end of its lifetime, it must be permanently plugged and abandoned. Such plug and abandonment (P&A) operations usually consist of placing several cement plugs in the wellbore to isolate the reservoir and other fluid-bearing formations. Permanent P&A of wells has been an important topic for several years (Calvert and Smith, 1994; Jordan and Head, 1995; Barclay et al., 2001), but there has been an increased focus in recent years which is probably due to the large number of old offshore wells in mature areas such as the North Sea and Gulf of Mexico (Liversidge et al., 2006; Saasen et al., 2013; Rassenfoss, 2014; Davison et al., 2017). Operators are now informally talking about an upcoming "P&A wave" of wells that need to be permanently plugged.

Depending on well conditions, P&A operations can however be quite time-consuming and thus very costly. Moreover, offshore wells are considerably costlier to abandon than onshore wells (Oil & Gas UK, 2015a). In the North Sea for example, approximately two thousand wells are planned to be permanently plugged and abandoned in the upcoming decade. Up to £3 billion each year is forecasted to be spent on decommissioning activities in the North Sea during the upcoming years,

where about 50% of these costs are on well P&A operations alone (Oil & Gas UK, 2016).

Furthermore, an essential aspect of P&A is to ensure well integrity after abandonment (King and Valencia, 2014). In earlier years, not too much emphasis was put on ensuring that wells were properly plugged since regulations covering P&A operations were vague and inadequate (NPC, 2011). Several old, plugged and abandoned wells are therefore leaking (Watson and Bachu, 2009; Vielstädte et al., 2015; Kaiser, 2017). Catalyzed by the 2010 Macondo accident and subsequent serious oil spill, changes in technology and regulatory regimes have caused the industry to make some significant shifts in their attitude towards P&A in recent years (Smith and Shu, 2013). The focus of P&A operations is now on environmental issues such as preventing leakages, in addition to cost-efficiency.

### 1.1. Plug and abandonment operations

Fig. 1 shows a simplified illustration of a typical production well before and after P&A.

The details of an operational P&A procedure may differ significantly from well to well, depending on the type of well and the actual well

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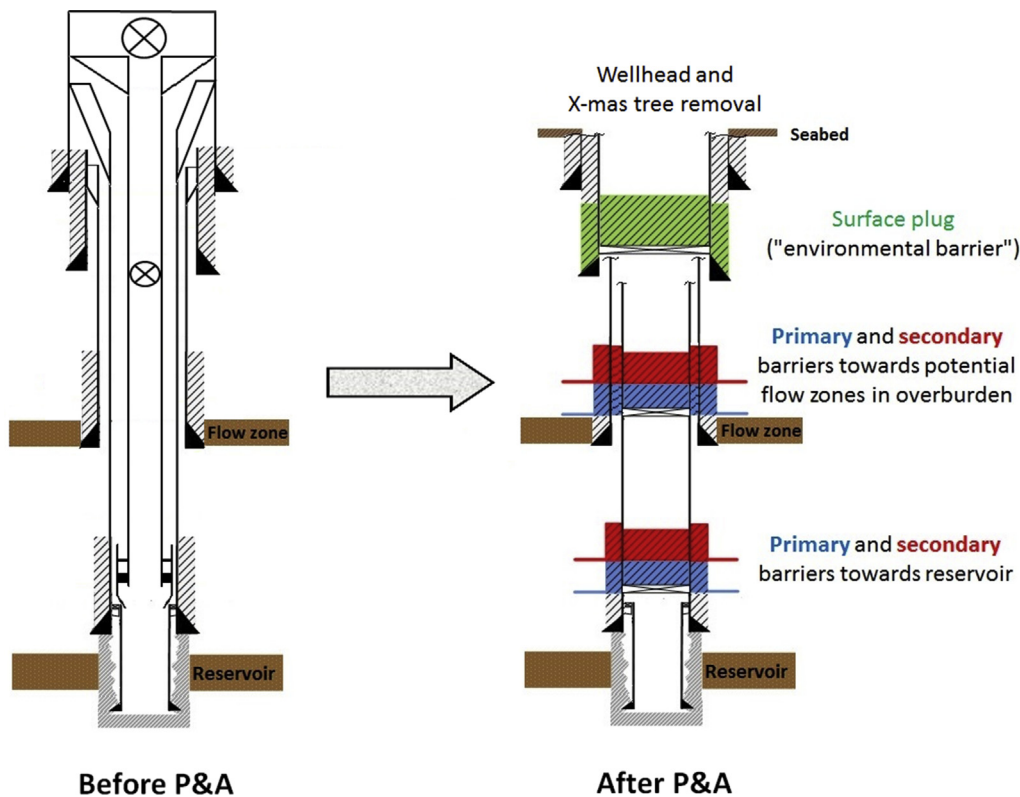


Fig. 1. Simplified illustration of a typical offshore production well before and after P&A. The colour coding of primary barriers (blue), secondary barriers (red) and surface plug (green) are based on current Norwegian well barrier definitions (NORSOK D-010, 2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

conditions. There are however several common steps, and a typical P&A operation can be briefly summarized as follows:

First, the well is prepared for P&A by circulating high density drilling fluid and installing deep set mechanical plug, before the barriers towards the reservoir are installed. A well-regulated area such as the North Sea requires two independent barriers towards the reservoir (NORSOK D-010, 2013; Oil & Gas UK, 2015b), where the primary and secondary barriers shall not have common well barrier elements. Secondly, any fluid-bearing formations in the overburden, such as high-pressure zones and hydrocarbon-containing formations, are also isolated with two independent barriers. Furthermore, an openhole-to-surface plug (also called the “environmental barrier”) is installed below the seabed, which prevents any residual fluid contamination to the environment. Finally, the conductor and wellhead are removed.

Oil & Gas UK (2015a) have divided the operational sequence of P&A operations into three distinct phases: Phase 1 is defined as “Reservoir abandonment” and includes installing primary and secondary barriers towards the reservoir. Phase 2 is defined as “Intermediate abandonment” and includes installing potential barriers towards flow zones in the overburden and the surface plug. Phase 3 is defined as “Wellhead and conductor removal” and includes cutting and retrieval of casing strings and conductor, as well as wellhead removal. In addition to these three phases, Moeinikia et al. (2014) have suggested to include a fourth phase as well, entitled Phase 0 “Preparatory work”, which includes pre-

P&A work such as killing the well and installing deep set mechanical plugs. Table 1 lists these different phases of the P&A operation and summarizes their respective contents.

An important benefit of dividing the full operational P&A sequence into different phases is that this approach highlights the opportunities for performing simpler parts of the P&A operation by rigless methods, instead of more traditional and costly rig-based methods. For example, for P&A of subsea wells, considerable costs can be saved by performing Phases 0 and 3 by a riserless well intervention (RLWI) vessel instead of a drilling rig (Sørheim et al., 2011; Moeinikia et al., 2015a; Varne et al., 2017a; Canny, 2017).

### 1.2. Potential leak paths in plugged and abandoned wells

Placing a cement plug in a cased wellbore is in most cases not sufficient to prevent leakages from the well after abandonment, as leakages may also occur in the annulus outside the casing. Especially for old wells where the annulus cement is likely to be damaged, since cracks and microannuli (i.e. debonding) may form in the cement sheath due to forces occurring in normal well operations such as pressure testing, injection, stimulation and production (Boukhelifa et al., 2005; Bois et al., 2011; Therond et al., 2017). For example, for a well after 30 years of CO<sub>2</sub> injection, prominent leak paths at both the cement-casing and cement-formation interfaces were found after coring (Carey et al.,

Table 1  
Different phases of P&A operations for typical well with vertical Xmas tree.

Operational phase	Contents
Phase 0: Preparatory work	Retrieve tubing hanger plugs, kill well, install deep set mechanical plug, punch/perforate tubing, circulate well clean
Phase 1: Reservoir abandonment	Rig up BOP, pull tubing hanger and tubing, install primary barrier with its base at top of influx zone (i.e. reservoir), install secondary barrier where the base of barrier can withstand future anticipated pressures
Phase 2: Intermediate abandonment	Remove casing strings (if necessary), install primary and secondary barriers towards potential flow zones in overburden, install surface plug (“environmental barrier”)
Phase 3: Wellhead and conductor removal	Cut conductor and casing strings below seabed to avoid interference with marine activity, retrieve casing strings, conductor and wellhead

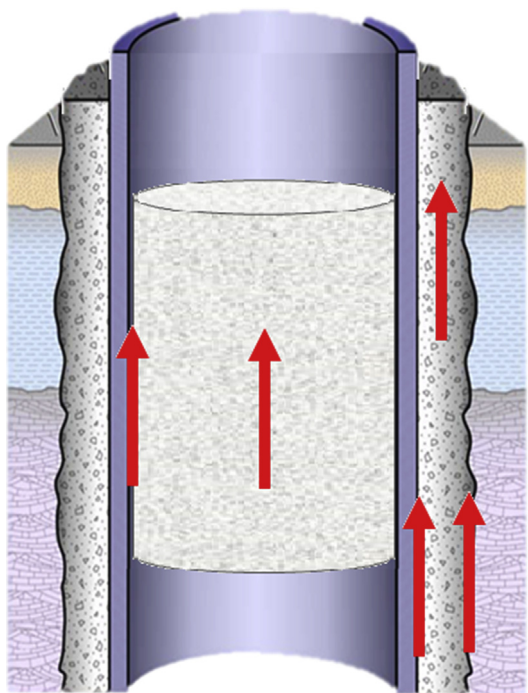


Fig. 2. Illustration of potential leak paths in a plugged and abandoned well: Through the cement or around the cement.

2007).

As illustrated in Fig. 2, there are several potential leak paths in a plugged and abandoned well (Gasda et al., 2004; Carrol et al., 2016; Kiran et al., 2017). For the cement plug, leakages may go through the plug itself, depending on cement matrix permeability or presence of internal cracks, or around the plug at the cement-casing interface, due to microannuli formation during cement shrinkage or poor mud removal. Similarly, for the annulus cement, leakages may go through the cement sheath, or around the cement sheath at the cement-casing interface or at the cement-formation interface. It is assumed that the casing itself does not represent a potential leak path, since it is covered and protected by cement at all sides, although this assumption may be incorrect in the extreme long-term.

Norwegian well barrier requirements therefore state that "permanent well barriers shall extend across the full cross section of the well" (NORSOK D-010, 2013), which means that the barrier starts and ends at the formation surrounding the wellbore and includes all annuli as well as the cement plug. For example, the primary well barrier envelope towards the reservoir shown in Fig. 1, consists of the in-situ formation, annulus cement, casing and cement plug. In other words, all these well barrier elements must seal sufficiently for the well to be properly abandoned, and if one of them fails the whole well barrier envelope is breached and the well may start leaking. The wellbore must therefore be sealed off from rock to rock, and this point has been elegantly expressed by Oil & Gas UK (2015b), when describing that the aim of P&A operations is "restoring the cap rock".

## 2. Plugging materials

Although Portland cement is by far the most commonly used plugging material, there are other types of alternative and emerging plugging materials (Oil & Gas UK, 2015c; Khalifeh et al., 2013). A description of some of these materials is given in the following, with an emphasis on Portland cement. Table 2 provides an overview of these different plugging materials.

### 2.1. Portland cement

Throughout history, setting materials have played an important role and were used widely in the ancient world (Blezard, 2007). For example, the Romans found out that a setting material could be made which sets under water and it was used for the construction of marine structures such as harbours. In 1824, Joseph Aspdin patented a setting material he produced by calcining a mixture of limestone and clay at 1450 °C. The cured produced material looked like Portland stone, a widely-used building stone in England and a building stone preferred by London's famous architect and church builder Christopher Wren, a century before Aspdin's invention. Because of the similarity with Portland stone, Aspdin called his invention "Portland cement".

The major components of Portland cement clinker, being the material leaving the cement kiln, are CaO, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and Fe<sub>2</sub>O<sub>3</sub>. The clinker mainly contains four major mineral phases: 50–70% tricalcium silicate (3CaO·SiO<sub>2</sub> or "C<sub>3</sub>S"), 15–30% dicalcium silicate (2CaO·SiO<sub>2</sub> or "C<sub>2</sub>S"), 5–15% tricalcium aluminate (3CaO·Al<sub>2</sub>O<sub>3</sub> or "C<sub>3</sub>A") and 5–10% tetracalcium aluminoferrite (4CaO·Al<sub>2</sub>O<sub>3</sub>·Fe<sub>2</sub>O<sub>3</sub> or "C<sub>4</sub>AF"). The calcium silicates are amorphous unstable material that will re-crystallise or develop stable amorphous forms after blending with water. First, there is a reactive period where water reacts with the mineral surfaces and creates a gel like layer that prevents further reaction. This creates a dormant period, i.e. an induction period, where it is possible to pump the cement. When the calcium concentration in the mix water is sufficiently over-saturated, further curing reactions occur and the calcium silicates and the mentioned gel starts to form and build strength, i.e. the cement sets to become a solid material. For the aluminates there are no dormant period. To control setting of these minerals, calcium sulphate minerals (gypsum, anhydrite, hemi-hydrate, etc) are added. As long as there is gypsum left, metastable crystals (ettringite) will be formed onto the aluminate, and an artificial dormant period is created. The ferrite phase reacts similarly as the aluminate but very much slower. For a more thorough description of cement curing, the reader is referred to *Lea's Chemistry of Cement and Concrete* (Hewlett, 1998) and Taylor (1992).

Use of Portland cement in well cementing is described by Nelson and Guillot (2006), and there are now several different types of Portland cement. In the early days of well construction, cement was a material available from the construction industry. Thus, in absence of other zonal isolation or plug back material, this cement was accepted without any of the present qualification programmes. Originally, plain construction cement types were used. Hence, these became API classes A, B and C cements, dependent on their reactivity and sensibility for other present materials. As the wells became deeper, and the temperature increased, there was a need for materials that did not solidify equally rapid. The simple solution was to grind coarser material. This would delay the cement thickening time, and the results were API classes D, E and F cement. As cement production technology developed, these types, D, E and F, are seldom used because specialised oil well cements for general application were developed; the API cement types classes G and H. The essential difference between these two types is again, fineness. Class G cement is somewhat finer than class H. These two cements dominate as material for current offshore cementing operations.

Portland cement is rarely used as neat cement without any additives, so a description of cement is incomplete without also mentioning necessary additives. These include:

- Barite, ilmenite, hematite or manganese tetra oxide to increase slurry density
- Bentonite (pre-hydrated or dry), hollow glass spheres or pozzolans to reduce density or increase cement yield (cemented volume per volume of cement)
- Microsilica or latex to make the cement slurry gas tight
- Silica flour to make the cement tolerant for temperatures above

**Table 2**  
Overview of different plugging materials; both currently used and alternative/emerging.

Plugging material	Description
Portland cement	Most commonly used plugging material worldwide. Consists mainly of calcium hydroxide ("portlandite") and various calcium silicate phases. Addition of selected additives enables a wide range of different specialised cement systems such as expandable cements and flexible cements.
Blast Furnace Slag (BFS)	This waste product from steel manufacturing process has been used in well cementing applications, by itself and as additive to Portland cement. Not widely used as plugging material.
Bentonite	Bentonite has been applied as plugging material due to its ability to swell and its low permeability.
Low melting point metal alloys	Bismuth containing low melting point metal alloys has been suggested as a potential plugging material. An advantage would be a good metal-to-metal bond to casings.
Thermosetting polymers (resins)	Resins are particle-free fluids which solidify into an impermeable material upon curing. The curing process is temperature-activated and occurs at a predefined temperature. Have been used as plugging material.
Unconsolidated sand slurries	Sand slurries as plugging material fills the well with a deformable, low porosity, non-permeable and non-shrinkable material, that is easy to remove. Well-suited for temporary abandonment, and has also been used for permanent abandonment.
Geopolymers	Geopolymers are a type of inorganic, rock-like, materials that can be described as "artificial stone". Were originally developed as construction material for the civil engineering sector but several laboratory studies have shown their potential in oil well applications as well, including as an alternative plugging material.
Thermite	Potential step-change technology where burning thermite is used to melt the casing, cement and rock to form an impermeable plug. A potential concern is whether any leak paths are formed around the plug after cooling.

110 °C

- Flexible particles to reduce stiffness and improve flexibility
- Expandable agents such as magnesium oxide and calcium oxide

These additives will affect both the short- and long-term properties of the placed cement volume as well as interfere with the placement itself. A brief review of cement additives has been given by Nelson et al. (2006).

## 2.2. Alternative and emerging plugging materials

### 2.2.1. Blast Furnace Slag (BFS)

Blast Furnace Slag (BFS) is a by-product of steel manufacture during operation of a blast furnace. The BFS is accumulated on top of the molten iron in the furnace, and consists of lime, silica, alumina, magnesia and iron oxides. Depending upon the cooling process, this waste product can be used as hydraulic binder material (i.e. cement), both by itself and as additive to Portland cement, and has been used in well cementing applications (Saasen et al., 1994).

In the late 1980s and the following years, a technique was developed for converting drilling fluid to cement. Cowan et al. (1992) developed the Mud-to-Cement system based on adding BFS to certain water-based drilling fluids, where BFS was used partly as weight material and partly as fluid loss control material. When cementing was to be performed, the BFS concentration was increased while alkali activators were added. The BFS formulated mud-to-cement was used in several onshore fields in Texas, US (Daulton et al., 1995). The initial response was that the cementing operations were reasonably successful, and the following offshore experience was similarly promising (Nahm et al., 1995).

Later, the drilling industry abandoned use of BFS in well cementing. According to Bensted (2007), this was because the cured slag cement was vulnerable for crack development. Furthermore, the logistics around the application was complex. The use of BFS as sole plug material may thus be limited. Also, the wide application of oil-based drilling fluid may restrict the use of BFS for cementing operations.

### 2.2.2. Bentonite

Concentrated bentonite has been applied as material for P&A of oil and gas wells due to its ability to swell and its low permeability (Englehardt et al., 2001; Clark and Salsbury, 2003). The material has been tested and used successfully for P&A operations in several wells in the US and Australia in recent years. According to Towler et al. (2016) laboratory tests have shown that the concentrated bentonite would re-heal itself if cracks occurred.

### 2.2.3. Low melting point metal alloys

Low melting point eutectic metals have been tested for removing sustained casing pressures both in presence of oil-based and water-based drilling fluids (Carpenter et al., 2004). Also, in the formulation of the low melting point eutectic metal plug, bismuth was one of the ingredients. This is beneficial for proper bonding to the well and pipe surfaces, since this metal expands significantly on solidification, thereby creating a good metal-to-metal bond. Recently, bismuth alloys have been suggested as plugging material for permanent P&A (Carragher and Fulks, 2018).

### 2.2.4. Thermosetting polymers (resins)

Thermosetting polymer (resins) are particle-free fluids which solidify into an impermeable material upon curing. The curing process is temperature-activated and occurs at a predefined temperature. In addition, viscosity and density can be tailored for various applications by addition of particles. Resins have been used as plugging material both in the North Sea and Gulf of Mexico (Beharie et al., 2015; Davis, 2017). With respect to durability, laboratory tests have shown a loss of strength in downhole environments such as crude oil and H<sub>2</sub>S (Beharie et al., 2015). Other uses of resins are in squeeze operations in the annulus between two casings to regain zonal isolation (Al-Ansari et al., 2015), and repair of casing leaks (Sanabria et al., 2016).

### 2.2.5. Unconsolidated sand slurries

Unconsolidated sand slurries have been used for permanent plug and abandonment (Saasen et al., 2011), and the permeability should theoretically be less than 0.01 mDarcy. The purpose of sand slurries as plugging material is to fill the well with a deformable, low porosity, non-permeable and non-shrinkable material. If a system with solely monodisperse particles was used, the maximum sand concentration would be just a bit larger than 50%, leaving the rest to a permeable pore volume. However, if particle sizes are selected carefully, it is possible to fill the pore volume with successively smaller particles, to create a high solids fraction slurry. These high solid fraction slurries will be easily mobile but will behave like a fluid with reasonably high yield stress.

Such a sand slurry was developed and originally qualified for temporary abandonment (Saasen et al., 2004), and it is well-suited for such an application due to its non-setting and thus easily removable nature. In this example, the sand concentration was around 80%. Care must be taken to hinder access to additional water, since addition of water can trig an internal segregation process that will make the sand slurry paste-like and thus not pumpable. Change of fluid properties must be conducted by addition of solids (Godøy et al., 2004).

### 2.2.6. Geopolymers

Geopolymers are a type of inorganic, rock-like materials that can be

described as “artificial stone”. They are alkali-activated aluminosilicate materials with low calcium content (Davidovits, 2011). Geopolymers are based upon different raw materials (i.e. precursor materials) such as fly ash, kaolinite and various types of rocks. By varying the type of raw material, different types of geopolymers with selected properties can be obtained.

Three main mechanisms are distinguished, which result in solidification of aluminosilicate material: dissolution or depolymerization, transportation or orientation and geopolymerization or polycondensation (Provis and van Deventer, 2009). In dissolution process, alkaline activator (known also as hardener) attacks precursor materials and depolymerizes the silicates. As a result, small species of inorganic polymer units, oligomers, are formed. These oligomers have the opportunity to be transported through the liquid phase and rearrange themselves. In the geopolymerization stage, these oligomers make covalent bonding together and form long chains of molecules, known as geopolymers. The geopolymerization process is a fast reaction and difficult to control.

Geopolymers were developed and are used as construction materials in the civil engineering sector (Davidovits, 2011), and has not yet been used in plug cement operations or other well applications. However, several studies have shown their potential as well cement material (Khalifeh et al., 2014, 2018; Salehi et al., 2017). Properties such as low shrinkage, low permeability, strength development, stability at elevated temperatures, and tolerance to contamination with oil-based mud (OBM), suggest geopolymers to be an alternative to Portland cement for many oil well cementing applications including P&A (Khalifeh et al., 2016, 2017; Salehi et al., 2016). There are currently some unanswered questions regarding their usability, such as controlling pumpability while optimizing waiting on setting. Others have observed self-healing properties of geopolymer solutions (Liu et al., 2017), which may be beneficial in a long-term perspective.

### 2.2.7. Thermite

A recent, emerging development from Norway is the potential use of thermite to permanently plug wells. To our knowledge, no publications exist yet that describes this procedure, although it was mentioned by Stein (2018). The concept is to initiate slow burning of a thermite plug at selected depth, which is an exothermic reaction that reaches thousands of degrees Centigrade. The reactants melt through the wellbore, including casing, cement and formation, and bond with the surrounding rock formation. After cooling, the result will be a solid and impermeable barrier that extends across the full cross section of the well.

This concept could be a major game changing P&A technology if it works as intended. At present, the technology is still under development and is being tested and validated. A potential drawback and current concern is whether the rock around the formed plug is damaged; i.e. if any leak paths are created around the plug after cooling.

## 3. Ensuring plug integrity

To fulfil the objective of “restoring the cap rock”, the plug itself must seal the wellbore and retain its integrity for the future. NORSOK D-010 (2013) lists the following characteristics of permanent well barrier materials, and a similar list is also given by Oil & Gas UK (2015b):

- Provide long term integrity (eternal perspective)
- Impermeable
- Non-shrinking
- Able to withstand mechanical loads/impact
- Resistant to chemicals/substances (H<sub>2</sub>S, CO<sub>2</sub> and hydrocarbons)
- Ensure bonding to steel
- Not harmful to the steel tubulars integrity

For simplicity, it is assumed in this section that cement is used as

plugging material, since cement is used in most plugging operations. However, most of the discussion is relevant for other plugging materials as well.

As shown in Fig. 2, potential leakages related to the wellbore plug can occur *through* the plug or *around* the plug. Leakages through the plug is mostly determined by the permeability of the plugging material. Chemical or thermal degradation of the plugging material due to downhole conditions may influence the integrity of the plug, and thus potentially increase the leak rate through the plug. Whereas leakages around the plug occurs between the plug and casing (or formation), i.e. in so-called “microannuli”, and could be caused by debonding due to shrinkage during cement curing or by poor mud removal during plug placement.

### 3.1. Plug placement

There are several methods available for placement of cement plugs inside wellbores and an overview of plug placement methods has been given by Daccord et al. (2006). Most commonly used is the balanced plug method, where cement is pumped through the work string and placed at the designated depth. However, placement of good cement plugs can be an operational challenge.

A critical issue during cement plug placement is to prevent flow of cement further down into the well, due to instabilities of the lower interface towards the fluid below caused by differences in density or viscosity (Calvert et al., 1995; Crawshaw and Frigaard, 1999; Malekmohammadi et al., 2010). This phenomenon is known as Rayleigh-Taylor instability. It is therefore important to have a good base or foundation for the cement plug to ensure good placement. Gel plugs or viscous pills have been used as foundation for cement plugs, but Harestad et al. (1997) has shown that the use of viscous pills underneath a denser cement will be insufficient to hinder downwards cement flow. Mechanical bridge plugs are often used as foundation and these devices ensure a good base for the cement. In fact, in some countries like Norway, the required cement plug length is halved when a mechanical plug is used as foundation (NORSOK D-010, 2013), since it is believed that the cement plug integrity will improve due to its good base. A disadvantage with this approach is that the bridge plug will resist the testing pressure after cement placement, and there is thus no method to directly verify the cement quality. A soft packer on the other hand, like the umbrella tool developed by Harestad et al. (1997), only prevents motion of the fluid across the packer, and therefore allows for pressure testing of the cement plug.

### 3.2. Durability of cement at downhole conditions

For wellbore plugs to retain their sealing ability over time, the plugging material should be unaffected by the ambient downhole conditions. In other words, the plugging material should not degrade thermally or chemically. Typical potentially detrimental downhole chemicals include CO<sub>2</sub>, H<sub>2</sub>S and hydrocarbons, but water (i.e. brine) should perhaps also be included to this list since it is usually always present downhole. The durability of plugging materials such as cement can be determined by performing controlled ageing tests in the laboratory, but as Zhang and Bachu (2011) have pointed out, the specific test conditions used in ageing tests can have a major impact on the obtained results. Care should therefore be taken when designing a test procedure for ageing tests, and Oil & Gas UK (2015c) has suggested a guideline on how to perform durability tests of plugging materials.

Durability of well cement in CO<sub>2</sub>-rich environments has been studied rather extensively in recent years as part of research on Carbon Capture and Storage (CCS), and the degradation mechanisms of Portland cement due to CO<sub>2</sub> are relatively well-known (Kutchko et al., 2007; Zhang and Bachu, 2010; Carrol et al., 2016). It is beyond the scope of this paper to give a comprehensive overview of this work, but a brief description of the degradation mechanisms can be summarized as

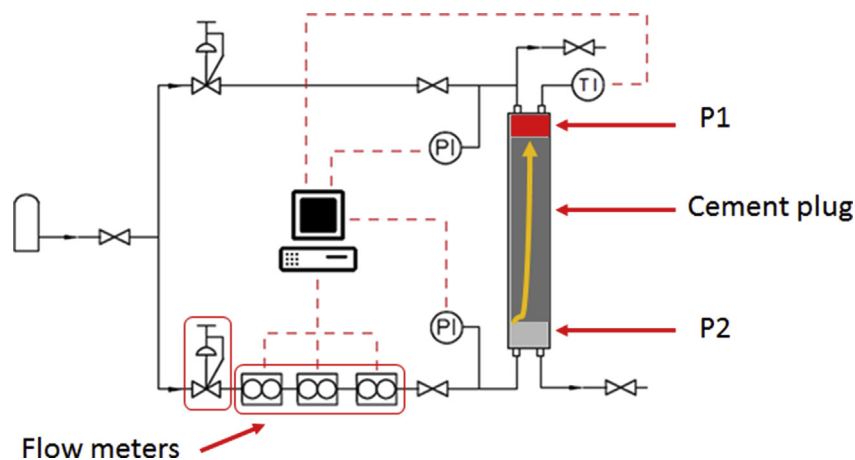


Fig. 3. Illustration of a typical laboratory set-up for determination of cement plug sealing ability: a cement plug is placed inside a steel casing with a pressure difference across the plug ( $P1 < P2$ ) and the resulting flow rate is measured by flow meters (After [Opedal et al., 2018](#)).

follows: Degradation of Portland cement by  $\text{CO}_2$  occurs in two main steps, where the first step is reaction of calcium hydroxide (portlandite) with  $\text{CO}_2$  where calcium carbonate is formed. This step is called “carbonation” of cement, and leads to a decrease in cement porosity and permeability, but not necessarily a decrease in mechanical properties. The next step is called “bi-carbonation” of cement, where calcium carbonate is dissolved in  $\text{CO}_2$ -rich (i.e. low-pH) water. The resulting silica-rich, degraded material is highly porous, which may be unsuitable as barrier material due to its high permeability. It should however be noted that since  $\text{CO}_2$  degradation of Portland cement is a diffusion-driven chemical reaction, the actual degradation kinetics is very slow and can thus be a self-decelerating process. For example, the decrease in permeability caused by the carbonation step significantly slows down the reaction rate of the second step, and local equilibria of  $\text{Ca}^{2+}$  ions inside pores also prevent the second degradation step (Zhang and Bachu, 2010). A full degradation of a cement plug of tens of meters by  $\text{CO}_2$  will therefore be extremely slow, i.e. occur over thousands or hundreds of thousands of years. Furthermore, the service industry has developed cement systems that are more  $\text{CO}_2$ -resistant than neat Portland cement ([Barlet-Gouédard et al., 2009](#); [Brandl et al., 2011](#); [Garnier et al., 2012](#)), by including selected additives such as different pozzolans and by decreasing the permeability of the cement matrix to decrease  $\text{CO}_2$  diffusion further.

There exist some durability studies of cement in other relevant downhole environments such as  $\text{H}_2\text{S}$  and crude oil as well ([Noik and Rivereau, 1999](#); [Lecolier et al., 2006, 2007](#); [Garnier et al., 2012](#)), but these studies are rather few. Recently, [Vrålstad et al. \(2016\)](#) performed durability tests of well cement in crude oil, brine and  $\text{H}_2\text{S}$ , respectively, at downhole temperatures and pressures. For crude oil, they found no significant effect on cement properties, which was consistent with the findings of [Lecolier et al. \(2007\)](#). For brine, they found an increase in volume (i.e. swelling), possibly due to further cement hydration, which indicates an improvement in sealing ability. For  $\text{H}_2\text{S}$ , they found a detrimental effect of the exposure; the cement decreased in weight and lost most of its mechanical strength. This is consistent with the findings of [Garnier et al. \(2012\)](#) and [Lecolier et al. \(2006\)](#) and is due to a process called “calcium leaching”, where the calcium hydroxide (portlandite) is dissolved by acid. However, [Vrålstad et al. \(2016\)](#) also found that the  $\text{H}_2\text{S}$  resistance of Portland cement was considerably improved when silica flour was included as additive, which was possibly due to the pozzolanic nature of silica. Cement additives may therefore improve the  $\text{H}_2\text{S}$  resistance of well cement. Furthermore, as for  $\text{CO}_2$  degradation,  $\text{H}_2\text{S}$  degradation of cement is also a diffusion-controlled process and actual degradation of a plug in the field will be quite slow.

Regarding ageing tests of cement and other plugging materials, it should be noted that most quantitative results obtained from chemical

degradation tests cannot be directly transferred to field conditions. This is because the chemical degradation reactions occur several orders of magnitude faster in laboratory ageing tests than in a well. In laboratory tests, the material samples are submerged directly into the reactive fluids, which creates a large reaction surface area and an unrestricted supply of reactive compounds. Whereas in the field, all reactive compounds (such as  $\text{CO}_2$  or  $\text{H}_2\text{S}$ ) have to diffuse through a porous material such as sandstone to be able to reach the reaction surface at the cement. Degradation reactions in the field are therefore diffusion-limited and occurs quite slowly. The quantitative results obtained from ageing tests can thus vary quite significantly, depending on how realistically the tests are performed. For example, [Zhang and Bachu \(2011\)](#) reviewed ageing tests of cement exposed to  $\text{CO}_2$  and found that the predicted carbonation depth after 30 years exposure varied between 1 mm to over 2500 mm. There is a need for more data on realistically performed ageing tests of cement, also over longer time periods than one year, to better understand the actual long-term durability of well cement. Recently, [Ichim and Teodoriu \(2017\)](#) reported the development and establishment of a cement repository that stores cement samples under downhole conditions for minimum 5 years, to improve the understanding of long-term behavior of cement.

### 3.3. Microannuli: leakages around plugs

Leakages around cement plugs occur through microannuli, where the cement has fully or partially debonded. Experimental determination of the sealing ability of cement plugs is in principle relatively straightforward, as illustrated in [Fig. 3](#): a cement plug is placed inside a steel casing with a pressure difference across the plug, and the corresponding fluid flow rate is measured.

Among the first to perform a systematic study on cement plug sealing ability were [Nagelhout et al. \(2010\)](#), who performed laboratory tests in both small-scale and large-scale on two different cement systems. They found that the measured leak rate depended on the radial scale of the cement plugs and that the leak rate increased with increasing pressure difference across the plug. Furthermore, for a non-expanding cement system, they found an “equivalent permeability” in the milli-Darcy range, which is considerably higher than the permeability of good cement and thus indicates that the measured leakage occurs through microannuli around the cement and not through the cement itself. However, they found a significantly improved sealing ability for an expanding cement system. Recently, [van Eijden et al. \(2017\)](#) further developed and improved the methodology described by [Nagelhout et al. \(2010\)](#), and they also provide more details on the laboratory set-up and experimental procedure. They describe both a small-scale set-up and a large-scale set-up, where plug size is 2 in.

diameter and 38 cm length in small-scale and 6 or 8 in. diameter and 114 cm in large-scale, and they also found that an effect of radial size on sealing ability; where small plugs seal better than large plugs (van Eijden et al., 2017). During sample preparation, the cement is placed inside a casing and left to cure for several days under N<sub>2</sub> pressure. At the start of the test, the pressure is decreased at one side of the plug, to obtain a pressure difference across the plug and to avoid potential ballooning of casing. The gas flow across the plug is subsequently measured by flow meters.

By using such a laboratory set-up and experimental procedure, it is possible to determine both the breakthrough pressure, i.e. the lowest required pressure difference needed for detecting a flow rate, and the “equivalent permeability”, i.e. the measured flow rate for different pressure differences. The sealing ability of a specific cement system can thus be determined in a systematic manner and different cement systems can be compared. Oil & Gas UK (2015c) has therefore included the small-scale and large-scale set-ups described by van Eijden et al. (2017) as examples on how to perform functions tests on zonal isolation for different plugging materials. Furthermore, Opedal et al. (2018) has also built a small-scale set-up based on the one developed by van Eijden et al. (2017) with the objective of performing systematic studies on cement plug integrity. Their initial findings show that the sealing ability of neat Portland cement plugs improve significantly when the cement has access to external water during curing (Opedal et al., 2018).

In addition to laboratory tests, cement plug integrity can also be estimated by modelling tools. For example, Bois et al. (2018) present a model that predicts the hydraulic integrity of cement plugs, where microannuli formation is predicted based upon cement shrinkage during hydration and the initial state of stress in cement. They show a sensitivity analysis that demonstrate that the hydraulic plug integrity is dependent upon different cement properties such as Young's modulus, and they validate their model with field data from pressure testing of cement plugs (Bois et al., 2018).

However, a challenge during modelling of microannuli leakages, is which geometry and thickness to use as input data. Is the microannulus uniformly present around the entire circumference of the plug, or not? It is often assumed that microannuli are homogeneous with a uniform thickness, and although incorrect, this assumption about microannulus uniformity is also used for simplicity in experimental studies when estimating corresponding “microannuli thicknesses” from leak rate studies (Boukhelifa et al., 2005; Nagelhout et al., 2010; Aas et al., 2016). Recently, x-ray computed tomography (CT) has been used to visualize and quantify cement integrity (Vrålstad et al., 2015; De Andrade et al., 2016; Skorpa and Vrålstad, 2018). It is found that microannuli and cracks in cement start from initial, random defects and that microannuli are not homogeneous nor uniform. Fig. 4 shows two such examples of CT visualizations of experimentally obtained cement microannuli and it is seen that the microannuli are non-uniform and somewhat random. Furthermore, Skorpa and Vrålstad (2018) performed CFD simulations of fluid flow through such experimentally obtained leak path geometries, and they found a non-linear (i.e. non-Darcian) relationship between pressure difference and flow rate for fluid flow through connected cracks and partial microannuli. However, there was a linear relationship when the microannulus was uniform (Skorpa and Vrålstad, 2018). Uniform microannuli therefore provide more easily predictable leak rates.

### 3.4. Risk-based approach to P&A?

An important issue regarding plug integrity is the plug length. Currently, requirements for plug length varies between different countries and regulatory regimes (Barclay et al., 2001; van der Kuip et al., 2011). In the North Sea for example, at the Norwegian side of the border the required plug length is 100 m (50 m if a mechanical plug is used as foundation), whereas the required plug length is 30 m (100 feet) at the UK side of the border.

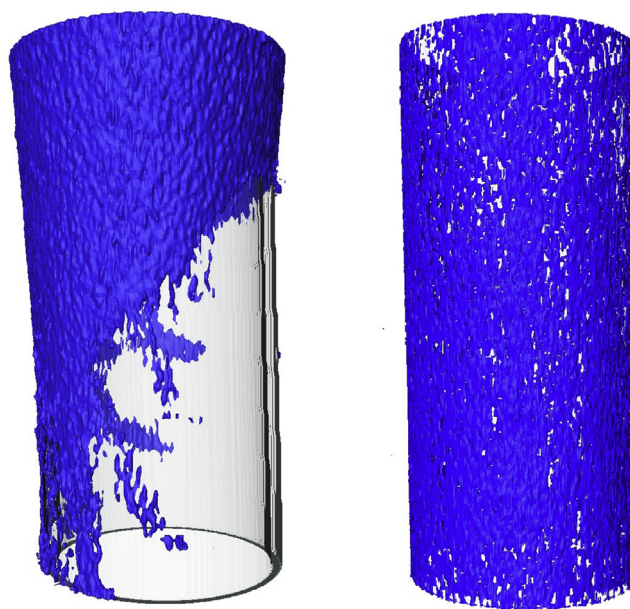


Fig. 4. Two different examples of x-ray computed tomography (CT) visualizations of experimentally obtained, non-uniform microannuli. The blue colour shows debonded cement. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

As an alternative to this “one-size-fits-all”, prescriptive approach to plug length (and the number of plugs), a risk-based approach to P&A has been suggested (Buchmiller et al., 2016; Fanailoo et al., 2017; Arild et al., 2017). This approach accounts for the fact that all wells are different with respect to for example flow potential and pressure difference, and provides a “fit-for-purpose” alternative. In such a risk-based approach, different P&A solutions are evaluated in terms of the probability that the permanent barrier system will fail within a given time-frame (Arild et al., 2017). The methodology for risk-based assessments consists of five steps: establishing the risk context, identifying well barrier failure modes, performing a risk analysis, performing a risk evaluation, and conducting qualification for well abandonment design (Buchmiller et al., 2016; Fanailoo et al., 2017). The P&A procedure can therefore be tailor-made to fit each unique well, and an advantage of such a risk-based approach is the potential for considerable cost savings, as less stringent requirements may be sufficient for “simple” wells. Furthermore, as an extension of this approach, the resulting leakage rates for different P&A scenarios may also be estimated (Arild et al., 2017; Ford et al., 2017; Ford et al., 2018). However, there is currently a lack of sufficient amounts of good quality experimental results that can be used as reliable input data to such models. For such an approach to be reliable, more experimental studies on plug sealing ability are needed.

## 4. Establishing annulus barriers

To obtain a full cross-sectional barrier from rock to rock, zonal isolation must also be ensured in the annulus. Fig. 2 shows that although the cement plug maintain its integrity, there are still several potential leakage pathways in the well, i.e. in the annulus. Such leakage paths in the annulus cement sheath are caused by formation of microannuli and radial cracks, which can form due to pressure testing and injection (Goodwin and Crook, 1992; Jackson and Murphey, 1993; Shadravan et al., 2015) and/or due to temperature variations during production and injection (Bois et al., 2011; Vrålstad et al., 2015; Therond et al., 2017). Such cement sheath failure is one of the reasons why many wells experience well integrity problems such as sustained casing pressure as they age (Bourgoyne et al., 1999; Vignes and

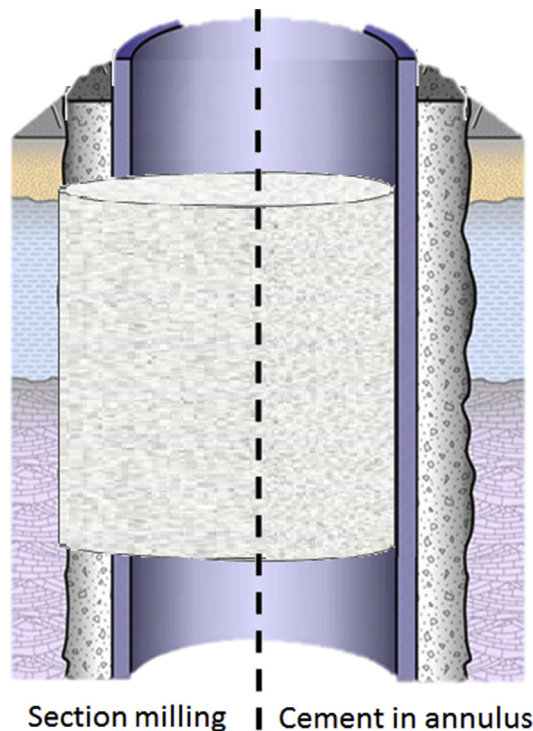


Fig. 5. Illustration of good annulus cement (right) and establishing annulus barrier by section milling (left).

Aadnoy, 2010).

If the annulus cement is of insufficient quality to be qualified as a barrier element for P&A, then this cement must be removed, or the barrier quality otherwise restored. Several methods and technologies exist for establishing annulus barriers, depending on whether the annulus is cemented and on the quality of the annulus cement, if present. The right part of Fig. 5 shows a cemented annulus of good quality, where the cement provides zonal isolation and there is no need for further action. However, if the cement is of poor quality, then the cement and casing must be removed by section milling before a cement plug is placed in the milled wellbore, as shown in the left part of Fig. 5. If the annulus is uncemented or poorly cemented, then the annulus can be cemented by the perforate-wash-cement method, which results in a cemented annulus as shown in the right part of Fig. 5. A special option exists for openhole, uncemented annuli, where creeping shale formation potentially can be used as annulus barrier. These methods will be discussed in more detail below.

#### 4.1. Section milling

Section milling is a method to create a cross-sectional barrier directly towards formation where the annulus material disqualifies as an annular barrier (Fig. 5 left). Special milling blades and cutters are used to mill out, i.e. remove, designated well sections in situations where the casing string is fully or partly cemented. Section milling is a time-consuming and thus costly operation, especially in regulatory regimes with substantial required plug lengths. The milling operation creates small metal cuttings called “swarf” that cause several operational problems. Swarf can accumulate as so-called “bird nests” in the well and if the bird nest occurs inside the BOP, it can damage the well control equipment and cause potential well integrity problems if the BOP malfunctions. Furthermore, the section milling tool can get stuck when pulling out of hole, and it should be noted that retrieved swarf at surface can create HSE problems.

Section milling is used in many P&A operations throughout the world and there is considerable focus on technology development to

increase milling efficiency and operational safety. Some examples include improvement of cutter and milling blade technologies (Scanlon et al., 2011; Stowe and Ponder, 2011), development of dual string section milling tools (Deshpande et al., 2016; McTiffen et al., 2017), saving rig time by single trips instead of dual trips (Hogg et al., 2014), and development of plasma-based tools (Gajdos et al., 2015). A recent development is the upwards milling tool (Joppe et al., 2017a; Nelson et al., 2018), which leaves the swarf in the well below the milled section and thereby probably avoiding swarf-related problems.

#### 4.2. Perforate-wash-cement

Perforate-wash-cement is a method that can be used to establish annulus barriers when the annulus is uncemented or partly filled with poor cement. The method consists of perforating the casing to obtain access to the annulus, washing the annulus with fluids to clean out mud, debris, settled barite or poor cement, and then subsequently pumping new cement into the annulus. There is thus no need to section mill or cut-and-pull the casing to place cement in the annulus, so the method can be very time efficient and cost effective (Ferg et al., 2011). In Fig. 1 for example, the perforate-wash-cement technique has been used to establish annulus barrier elements as part of the primary and secondary barrier envelopes towards the flow zone in the overburden.

The perforate-wash-cement technique is routinely used by several operators during P&A operations in the North Sea (Ferg et al., 2011; Stokkeland et al., 2017; Joneja et al., 2018) and has also been used to establish annulus barriers in wells in the Middle East (Ansari et al., 2016a, 2016b; 2017). Furthermore, Norwegian operators have developed barrier acceptance criteria for the perforate-wash-cement process, which is suggested for implementation in NORSOK guidelines (Delabroy et al., 2017).

#### 4.3. Shale as annulus barrier

In well sections running through shale formations, it is occasionally found that the annulus is closed even though it was left open during the completion process (Williams et al., 2009; Fjær and Larsen, 2018). This is revealed by sonic or ultrasonic logs that can distinguish between solid and fluid behind the casing (Allouche et al., 2006; Wang et al., 2016; Fjær and Larsen, 2018), and the sealing efficiency of these naturally occurring barriers can be verified by pressure tests. Such “shale barriers” may extend over hundreds of meters along the well and eliminates the need for additional sealing of the annulus. This simplifies the plugging operations and implies significant cost reductions during P&A operations. For example, operators in Norway are currently routinely using shale as annulus barrier (Williams et al., 2009; Kristiansen et al., 2018), thereby considerably reducing their costs during well abandonment.

A shale barrier is formed as the rock surrounding the borehole is pushed towards the casing by the compressive in situ stresses. In other words, the shale “creeps” into the casing and thus fills up the annulus. This process has been reproduced in downscaled laboratory tests (Fjær et al., 2018) where it has been found that the ability of different shales to form a sealing barrier depends upon the properties of the respective shale such as mineral composition and mechanical properties. Furthermore, post-test micro-CT scans show that the rock in the vicinity of the hole has suffered a permanent, plastic deformation (Fig. 6). The micro-CT scans also reveal that the permanently deformed region extends several borehole radii into the formation. The porosity of this deformed region is higher than that of the intact shale, hence the permeability of the shale barrier tends to be higher as well. The sealing efficiency of a shale barrier is therefore less than it would have been if the space around the casing were filled with intact shale. However, the relevant comparison is rather with the realistic alternative, that the annulus is filled with cement with permeability that is typically 3–4 orders of magnitude higher than the intact shale (Fjær et al., 2018).



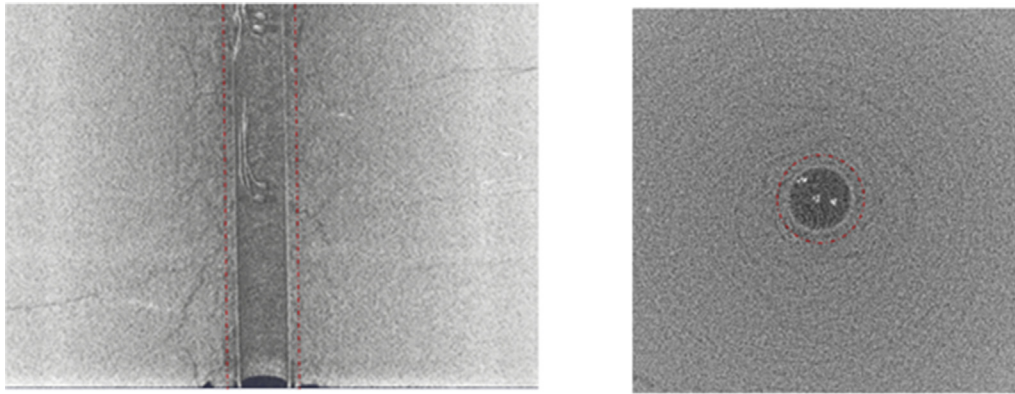


Fig. 6. micro-CT images of a shale barrier, formed in a laboratory test on a field shale core. Side view (left) and top view (right). The red dash-dot lines indicate the hole size prior to the test. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Annulus closure due to formation creep is a well-known process in salt formations (Willson et al., 2003). However, salt behaves essentially like a highly viscous fluid and will in the end always close the annulus given reduced annulus pressure and sufficient time. Shale on the other hand has a finite shear strength and is able to maintain a stable arch around the hole if the in situ stresses are not too high. Even if the arch is broken, the shale may not be able to establish a sealing barrier, as the rock may break up into separated pieces rather than deforming uniformly maintaining a low permeability. However, self-sealing may to some extent occur in fractured shale due to creep and various other mechanisms (Blümling et al., 2007; Bock et al., 2017). Over time, the sealing efficiency of a shale barrier is therefore likely to improve rather than deteriorate.

## 5. Casing cut and pull

Occasionally, during P&A and slot recovery operations, there is a need to remove a casing string fully or partly. Section milling can be used for this operation, but an alternative and sometimes preferred method is to cut and pull the casing (Abshire et al., 2013; Obodozie et al., 2016). However, a major problem that can occur during casing cut and pull operations is that the casing can get “stuck” due to settled barite in the annulus outside the casing (Joppe et al., 2017). For example, a North Sea operator recently needed nearly 40 cuts and over 70 days to cut and pull 3000 m of a single production casing from one well (Abshire et al., 2013).

Settled barite is a sediment phase that is formed during gravity separation when the drilling fluid is left static in the annulus for several years. The number and properties of different sediment phases that are formed during gravity separation depend the type of drilling fluid (Vrålstad et al., 2018). It is likely that friction and/or bonding between the sediments and casing create a significant portion of the problems when trying to pull the casing. However, it is also quite possible that the casing collars could be the most important cause of the stuck casing. For example, recent laboratory tests on casing pulling have shown that casings without collars are significantly easier to pull than casings with collars (Taghipour et al., 2018). This point is illustrated in Fig. 7: If the annulus sediments do not “flow” around the collars when the casing is pulled upwards, the casing is stuck. The consistency and rheological properties of the sediments can therefore determine how easily the casing is removed (Vrålstad et al., 2018).

Due to such problems with stuck casing, the service industry develops technologies such as downhole hydraulic pulling tools and other improvements (Abshire et al., 2013; Hartman et al., 2017; Melder et al., 2017). Recently, Joppe et al. (2017b) presented case studies with different methods of casing removal. The considered methods were use of jack-up rigs, rig-less intervention systems and jacking units. They concluded that the optimal solution must be selected based the availability

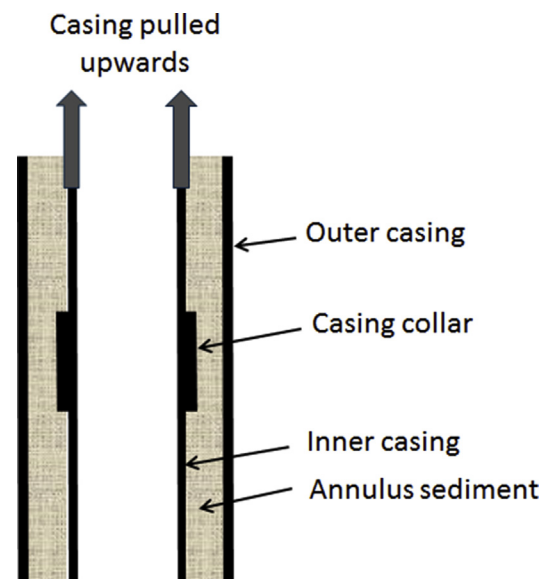


Fig. 7. Schematic illustration of possible cause of stuck casing during casing pulling operations: if the annulus sediment (settled barite) does not flow around the casing collars during pulling, the casing is stuck (After Vrålstad et al., 2018).

of tools, actual scope and the capabilities of the surface equipment. Pre-planning on a detailed level was emphasized as crucial, since cost escalation due to unforeseen events can be a challenge that prevents cost-effective solutions.

## 6. P&A of subsea wells

Subsea wells are different from platform wells in several ways that affect P&A operations. For example, due to the wellhead arrangements on subsea wells, it is only possible to monitor the annulus pressure between the production tubing and production casing, i.e. the A-annulus, and not possible to monitor the pressures in the outer annuli, i.e. in B- and C-annuli. The well integrity status of subsea wells is therefore partly unknown prior to P&A, which may significantly affect encountered problems during P&A operations and thus resulting durations. Technologies for wireless monitoring of B-annulus pressure is therefore currently under development (Rodriguez et al., 2017).

However, the main difference between platform wells and subsea wells is the “wetness” of the x-mas trees, i.e. subsea wells have the x-mas tree and all their production equipment at the seabed. Subsea wells therefore require mobile offshore units (MOU) such as semi-submersible drilling rigs to perform P&A operations. Due to the high spread rates of such units, subsea P&A operations can be much costlier than

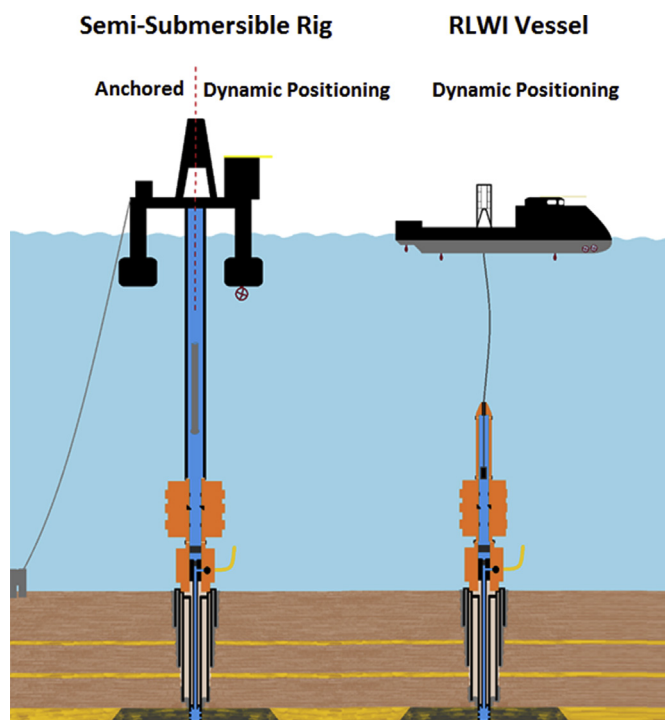


Fig. 8. Illustration of subsea P&A with semi-submersible rig and RLWI vessel, with respective available positioning alternatives (After Øia et al., 2018).

platform P&A operations (Oil & Gas UK, 2015a).

### 6.1. Use of rigs vs vessels for subsea P&A

Several field examples have shown that considerable cost savings can be obtained by performing part of subsea P&A operations with lighter vessels such as riserless light well intervention (RLWI) vessels instead of drilling rigs (Sørheim et al., 2011; Varne et al., 2017a; Canny, 2017). The technologies used for subsea P&A by RLWI vessels, such as well control package, lubricator and RLWI stack, are essentially the same as those used during conventional subsea riserless well interventions (Munkerud and Inderberg, 2007; Jøssang et al., 2008; Fjærtøft and Sønstabø, 2011; Varne et al., 2017b).

Regardless of type of MOU, the unit must adjust and hold its position to ensure that it is in-line with the subsea wellhead before and during a P&A operation. This is achieved either by anchoring or with an integrated dynamic positioning (DP) system. Fig. 8 shows a simplified illustration of use of rig and vessel for subsea P&A, where these two positioning approaches are included. A semi-sub rig can hold its position by either being anchored (depending on water depth) or by a DP system, whereas a RLWI vessel only relies on DP system. A significant difference between a semi-sub rig and a RLWI is the well control equipment and how they securely connect to a subsea well to allow fluid transport and intervention, as briefly illustrated in Fig. 8. The semi-sub uses a subsea BOP together with a workover riser (for high pressure) or a marine riser (for low pressure) to act as a conduit and ensure safe operations, whereas the RLWI vessel uses a riserless system.

As described in Table 1, the Oil & Gas UK (2015a) has divided the operational sequence of P&A operations into three different phases; Phase 1 “Reservoir abandonment”, Phase 2 “Intermediate abandonment” and Phase 3 “Wellhead and conductor removal”. In addition, a fourth phase, Phase 0 “Preparatory work”, has been suggested as well (Moeinikia et al., 2014). Furthermore, it can also be convenient to divide Phase 2 into two parts as well, where Phase 2a consists of placing primary and secondary barriers towards flow zones in the overburden (i.e. “overburden abandonment”), and Phase 2b consists of placing the

Table 3

Current applicability of semi-submersible rig, riserless well intervention vessel (RLWI) and light construction vessel (LCV) for different phases of subsea P&A operations.

P&A operational phase	Semi-sub rig	RLWI	LCV
Phase 0: Preparatory work	OK	OK	Not ok
Phase 1: Reservoir abandonment	OK	Not ok	Not ok
Phase 2a: Overburden abandonment	OK	Not ok	Not ok
Phase 2b: Openhole-to-surface plug	OK	OK	Not ok
Phase 3: Wellhead and conductor removal	OK	OK	OK

openhole-to-surface plug. Such an approach of dividing the full P&A operation into different phases and sub-phases is especially fruitful for subsea wells, since it elucidates the possibility for cost reductions by moving parts of the P&A operation to lighter vessels. Table 3 lists all these phases together with which type of MOU that can be used for the respective P&A work (based upon present technology). A semi-sub rig can be used for all phases of P&A operations, whereas a RLWI vessel can normally be used for all phases except Phases 1 and 2a, since these usually require drill string and heavy lifting capacity to perform operations such as section milling and pipe pulling. A simple operation such as wellhead and conductor removal, that does not require well control equipment, can be performed by a light construction vessels (LCV). It should be noted that the operability is higher for semi-sub rigs than light intervention vessels, allowing semi-subs to operate through the winter season with less waiting on weather (WOW).

### 6.2. Planning and coordination of multi-well P&A campaigns

Since subsea wells are located at different locations around the seabed, and not located at a single point, i.e. a platform, then the MOU must physically move from wellhead to wellhead (or template to template) to perform the necessary operations. This continuous MOU relocation is time-consuming and significant time and thus costs can be saved by abandoning several adjacent subsea wells together in multi-well campaigns. For example, Clyne and Jackson (2014) present a field case where 19 subsea wells were abandoned together in two consecutive multi-well campaigns. As lessons learned, they emphasize the need for thorough preparations and planning, the importance of knowing the well integrity status of the wells prior to P&A, and to use light vessels with ROV for pre-P&A work and for removing the wellhead (Clyne and Jackson, 2014).

This final point on using light vessels for parts of the P&A operation highlights a logistical advantage when performing multi-well P&A campaigns: it is not necessary to perform full P&A on one well before moving to perform full P&A on the next well, it can be more efficient to separate the operations into the different phases listed in Table 1, where each respective phase for all wells is performed before moving on to the subsequent phases. Such an approach enables use of different types of MOUs for the different P&A operational phases as described in Table 3. For example, a multi-well campaign could start with a RLWI vessel performing Phase 0 for all the wells, a semi-sub rig performs Phases 2 and 3 for all the wells (perhaps several months later, depending on rig availability), and then finally an LCV or RLWI vessel performs Phase 3 for all wells at a suitable time, depending on vessel availability and weather conditions. Sørheim et al. (2011) emphasized such an approach when they used a dedicated light vessel to cut and retrieve the wellhead from a subsea well, i.e. Phase 3. They estimated that it was not cost efficient to use a dedicated vessel to remove the wellhead from only one well, but if two or more wellheads were removed together in a multi-well campaign then the use of such a dedicated vessel was cost beneficial (Sørheim et al., 2011). Moreover, Varne et al. (2017a) exemplify this approach when they performed pre-P&A work (Phase 0) on several subsea wells for a Norwegian operator before a semi-sub rig performed the remaining P&A operations.

However, accurate time and cost estimations for the operational sequence are crucial during planning of multi-well P&A campaigns. Moeinikia et al. (2014; 2015a; 2015c) developed a probabilistic Monte-Carlo simulation tool that estimated time and cost-savings of rig-less P&A technologies for subsea wells. They used this approach to demonstrate the cost efficiency of performing Phases 0 and 3 by RLWI vessels instead of rigs. Furthermore, Aarlott (2016) and Bakker et al. (2017) introduced methods from operations research by using an optimization model for P&A planning of a simple subsea field. The optimization approach allows planners to evaluate how different strategies for vessel allocation, changed rental rates and effects of improved technology affect decisions and the impact on total cost. Due to the large number of possible scenarios when considering use of both semi-sub rigs and light vessels for a multi-well campaign, an optimization model can analyze the different possible scenarios and suggest optimal solutions for MOU allocation and routing for the entire campaign (Bakker et al., 2017).

### 6.3. Full P&A of subsea wells by RLWI vessels?

Further costs could perhaps be saved if all phases of the P&A operation were performed by a light vessel instead of a rig. As seen from Table 3, it is currently not feasible to perform the full P&A operation with a RLWI vessel. It could however be possible in the near future, and Valdal (2013) described potential scenarios for such an approach. Recently, Øia et al. (2018) presented several constructed cases on how existing technologies could be used for full P&A of subsea wells by RLWI vessels. They found that for wells of low to medium complexities, it could be possible to perform full P&A by using RLWI vessels, but for complex wells where for example section milling and heavy lifting is required, a semi-sub rig is still needed. They also found that although considerable costs could be saved by performing the operation by RLWI vessel instead of semi-sub rig, the semi-sub would in most cases be the least risky option, due to the large uncertainties in time estimations for RLWI vessel P&A operations (caused by the lack of experience for these operations).

A prerequisite for full P&A by RLWI vessel will in many cases be that the production tubing is left in the well, due to the limited lifting capacity on most vessels. If achievable in practice, then considerable costs can be saved by not removing the tubing (Moeinikia et al., 2015b). If the tubing string is left in the well, then the control lines will constitute a potential leak path (Dahmani and Hynes, 2017). The control lines must therefore be cut or retrieved, or the barrier placed at a depth with no control lines. Furthermore, a potential challenge with leaving tubing in the well, will be to place cement in the annulus between the tubing and casing, since the tubing is not centralized. However, Aas et al. (2016) have shown by large-scale experimental tests that it is possible to obtain good cement placement in this annulus when the tubing is left in hole.

## 7. Conclusions

To fulfil the objective of "restoring the cap rock", permanent barriers in plugged and abandoned wells must extend across the full cross section of the well. This includes establishing proper annulus barriers and preventing leak paths such as microannuli around plugs, which may cause P&A operations to be time-consuming. However, recent technology developments such as the perforate-wash-cement technique and utilizing shale as annulus barrier have significantly reduced the time spent on P&A operations. Furthermore, risk-based approaches to determining plug length and the number of plugs may further reduce time-consumption while maintaining well integrity.

There is still need for further technology developments however. Operators, service companies, vendors, research institutes and universities are all working on reducing risk of leakages, developing new technologies and improving P&A operations further. For example, while cement has been used as plugging material for a century and new and

improved cement systems are still being developed, completely new plugging materials and approaches such as bismuth-alloys and burning termite may perhaps change the industry. And in a few years' time, it may be possible to perform full P&A of subsea wells without using a drilling rig.

## Acknowledgements

This paper was prepared as a part of the project "Economic Analysis of Coordinated Plug and Abandonment Operations" (ECOPA), financed by the Research Council of Norway through the PETROSAM2 and PETROMAKS2 programs (p-nr: 247589). Also, the authors acknowledge the Research Council of Norway, Aker BP, ConocoPhillips, Equinor and Wintershall for funding part of the work through the research centre SFI DrillWell.

## Abbreviations

API	American Petroleum Institute
BFS	Blast Furnace Slag
BOP	Blowout Preventer; CFD Computational Flow Dynamics
CT	x-ray Computed Tomography
DP	Dynamic Positioning
HSE	Health, Safety and Environment
LCV	Light Construction Vessel
MOU	Mobile Offshore Unit
P&A	Plug and Abandonment
RLWI	Riserless Light Well Intervention
ROV	Remotely Operated Vehicle
WOW	Waiting on Weather

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