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Estimation of Plugging and Abandonment Costs Based on Different EU Regulations with Application to Geothermal Wells

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ABSTRACT

This paper presents the cost of plugging and abandonment (P&A) of the Horstberg Z1 well and shows how the well history is considered in the P&A planning process together with existing European regulations. Three different design plans are presented, based on innovative ideas and best practices in the oil and gas industry. Horstberg Z1, located in Germany, was originally a gas well, converted to a scientific geothermal well to prove the single well concept. After serving as a geothermal well for several years, the well has been proposed for P&A. The three designs presented in this work fulfill the purposes of well P&A, and meet the BVOT requirements, which are standard requirements for wells in Lower Saxony, Germany. Following a financial analysis of the designs, it is noted that rig costs are the largest element of the total expenditure, contributing over 50% in the design plans considered. As the number of cement plugs and round trips increase per design plan, the implementation period also increases, which impacts on the total cost. Based on the investigations made in this project, a minimum of USD 1,275,500 is required for the plug and abandonment cost of the well, excluding the well site re-cultivation. A rigless solution for pulling heavy casing out of the wellbore, to avoid the use of a conventional workover rig, would significantly reduce the plug and abandonment cost of the Horstberg Z1 well.

1. INTRODUCTION

As more and more brown fields reach the end of their productive life, maximizing economic recovery of hydrocarbons left in the reservoir and the safe, cost-effective abandonment of the wells which can no longer produce, will continue to be an integral goal for the oil and gas industry (Arugha et al., 2014; Liversidge et al., 2006). An oil and gas well will inevitably move from being an asset to a liability at the end of its life cycle (economic limit) or when the well sustains irreparable damage (Segura and Haq, 2012). At the end of a well's life, decommissioning is a major task for the operator, which has no return (i.e. it is not an investment, but pure cost), yet requires careful planning and execution to minimize risks that may lead to an increase in operational expenditure. Therefore, P&A, as a part of decommissioning, requires careful preparation and implementation. The oil and gas industry seeks optimal methods to P&A wells, because poorly abandoned wells pose serious financial and HSE risks.

The paper shows the step by step approach to estimate the P&A cost of the Horstberg Z1 well. The status quo of the well is presented and the guiding regulations of Germany, the Netherlands, Norway and the United Kingdom in designing the abandonment plan are reviewed and compared. Different abandonment designs are presented, analyzed, and compared to select the most effective and economic P&A option.

2. HORSTBERG Z1 WELL INFORMATION

The Horstberg Z1 well is located 80 km North-East of Hannover (Huenges and Ledru, 2010; BGR, 2016) and as a research well, all data are in the public domain. The well was originally drilled as a gas producer by BEB in 1987, but in 1990, after some tests were carried out, the well was shut-in because it was not economically viable to continue natural gas production. In 2003, the rights for geothermal energy exploration/testing were acquired by the German Federal Institute for Geosciences and Natural Resources (BGR). Before the well was transferred from BEB to BGR, the gas bearing Rotliegend sandstone formation was completely sealed off by plugging back the wellbore from 4918 m to 4120 m (Huenges and Ledru, 2010; BGR, 2016). The Middle Bunter sandstone formation, between 3636 m and 3926 m, was selected as the zone of interest for subsequent investigations of its geothermal energy potential, because of its large areal extent in the Northern German Basin and its high temperature at this depth (Huenges and Ledru, 2010). The final depth was reached with a wellbore diameter of 8 1/2" and a production casing of 7" diameter was installed. Along the wellbore, a maximum inclination of 12° at 3,614 m depth and an average inclination of 4.5° were recorded. At present, the wellbore is filled with cement from total depth up to 4,134 m, and a 7" bridge plug is set above the top of cement at 4,120 m (Huenges and Ledru, 2010; BGR, 2016). The Solling horizon is above the packer, while the perforations in the Detfurth formation below the packer are hydraulically activated (as shown in **Figure 1**). The sections perforated in the horizons of interest are shown in **Table 1**.

Table 1 - The perforations in each horizon (Huenges and Ledru, 2010; BGR, 2016)

Horizon	Perforations in borehole section (m)
Volpriehausen	3,920- 3926.6
Detfrurth	3,787- 3,791
Solling	3,655-3,673
Muschelkalk	3,037.5– 3,041.5 (closed)

3. PLUGGING AND ABANDONMENT FUNDAMENTALS

Abandonment operations can either be temporary or permanent, where the former is done with the intention of future re-entry of the well, which is sometimes referred to as 'suspended'. The plugging material employed should ensure an integrity period that is double the planned abandonment period (Norsok, 2004). The design idea of a permanent well abandonment has an everlasting perspective (i.e. design to last forever), so the well barriers put in place during P&A operations are intended to be established permanently. There are several stated P&A objectives that should be met to ensure that the wells are abandoned permanently (BP, 2008; Charles and Ronnie, 1999; IEA, 2009), and these include:

- compliance with government regulatory requirements,
- protection of freshwater sources penetrated by the wellbore,
- prevention of surface pollution,
- use of salvageable well components, and
- prevention of hydraulic communication between two distinct permeable zones penetrated by the wellbore.

An acceptable barrier for permanent abandonment must meet certain criteria (BP, 2008; Charles and Ronnie, 1999) as listed below:

- low permeability (< 1 mD),
- long term mechanical stability,
- strength and/or ductility to accommodate mechanical load or formation movements,
- provide a permanent seal with both casing and formation interface,
- resistant to different chemicals and substances (H_2S, CO_2, and hydrocarbons), and
- non-shrinking behavior.

Materials for Plugging Operations: The types of materials used for plugging abandoned wells have not changed significantly over the years. The most frequently used material for plugging wells is oilfield cement, which is often used in conjunction with drilling fluid, bentonite and mechanical plugs (Charles and Ronnie, 1999).

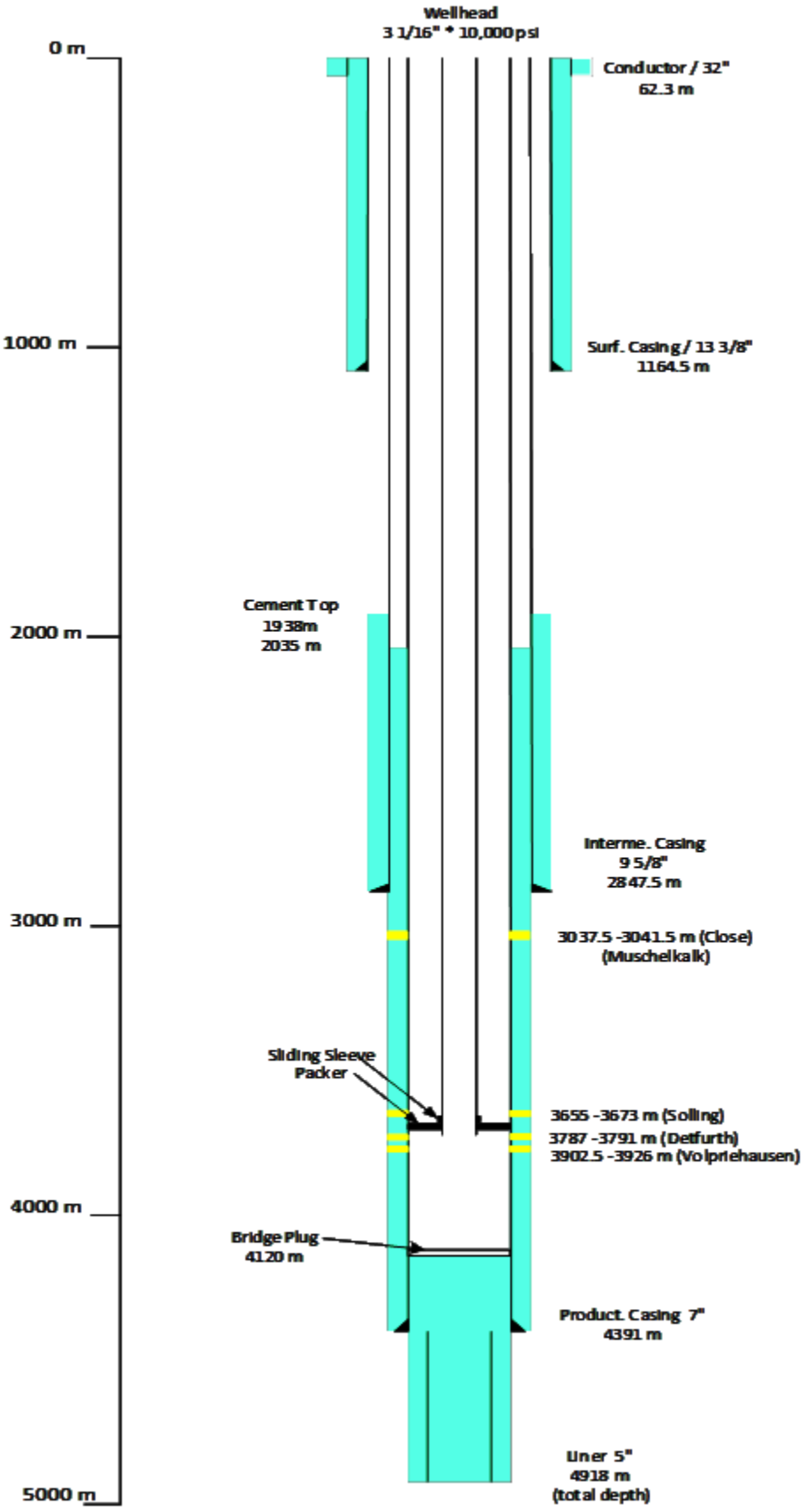


Figure 1 - Horstberg Z1 Well Schematic (Huenges and Ledru, 2010)

4. A COMPARISON OF ABANDONMENT REGULATORY REQUIREMENTS

In Germany, the P&A guidelines are given by the Deep Drilling Ordinance (BVOT), which apply to both complete and partial plugging of wells. According to §11 BVOT, abandoned wellbores are to be plugged so that the earth's surface will not subside (BVOT, 1998). In the operation plan on plugging, the following must be described, (i) the reason for plugging, (ii) the planned depth interval of the fill back zone/portion, (iii) the proposed plugging materials and, where appropriate, (iv) the kick-off depth, as well as areas where technical drilling difficulties occurred, with the aim of securing the plugging (BVOT, 1998).

It is required by law in Germany, Netherlands, Norway and United Kingdom, that the last operating company pays the well abandonment cost and is responsible for any leakage and subsequent clean up (Liversidge et al., 2006). Yet, technical and financial requirements differ on a country-by-country basis. For example, in the United Kingdom territorial waters, P&A of wells are done in accordance with the United Kingdom Offshore Operators Association (UKOOA) guidelines for suspension and abandonment of wells. In the Norwegian territory, NORSOK D-10 standard guidelines must be followed. In the Dutch territory, the Dutch mining authority guidelines must be obeyed. In the German territory, the Deep Drilling Ordinance (BVOT) guidelines must be followed.

Despite disparities of regulatory guidelines in various countries, all have similar objectives, which are to (i) prevent hydrocarbon leakage to the surface, (ii) prevent migration between different horizons, (iii) prevent contamination of aquifers, (iv) prevent pressure breakdown of shallow formations (Liversidge et al., 2006).

4.1. DIFFERENCES BETWEEN THE GERMAN GUIDELINES AND OTHER COUNTRIES

It is not required in the UK territory, for a cement plug to extend below the reservoir, unlike in the German territory, where a cement plug is expected to extend at least 50 m above and below the reservoir zone. The general requirements for both UK and Germany are presented diagrammatically in **Figure 2**. The squeeze cementing of perforations is not required in the UKOOA guidelines (Liversidge et al., 2006), since placing a cement plug in the reservoir zone is optional (IEA, 2009).

The NORSOK guidelines do not accept annular plugs as means of permanent abandonment; it is generally required that the casing be cut and pulled out, so that a wellbore plug can be set. The use of explosive cutters is prohibited, but mechanical cutters are permitted. This is because the explosive cutter has a higher potential to cause well integrity issues, like weakening the adjacent cement sheath and casing. The Dutch mining authority guidelines have similar principles to the German Deep Drilling Ordinance guidelines. All the guidelines give specific properties for the plugging material and require wells' initial design to consider final abandonment (Liversidge et al., 2006).

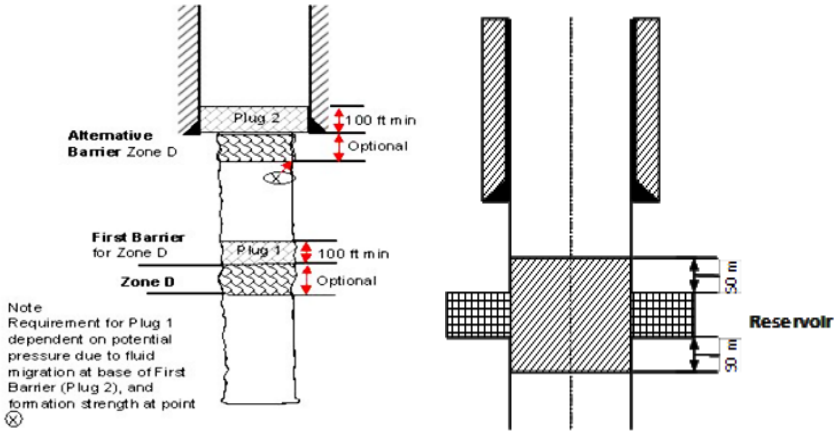


Figure 2 – General requirements for abandonment in the UK (left) and in Germany (right) (IEA, 2009; BVOT, 1998)

4.2. THE AREA BELOW THE SURFACE

The hole must be backfilled from Earth's surface down to a depth of 100 m with a special filling line. If a fresh water horizon is located below this interval, then the special filling line will be extended accordingly. All casing strings must be removed from all boreholes so that a later use of the ground (subsurface) will not be impeded. For wells in coastal waters and in the continental shelf, all casing strings extended up to about 5 m below seabed must be removed (BVOT, 1998).

The head or top of the special backfill line shall be determined by suitable methods. The quality of the seal must be proven when an open reservoir is sealed and no mechanical seal is used. The seal testing can be done by pressure test, flow test (inflow test) or weight sample. After completion of the backfilling job, the P&A report together with the modified wellbore diagram must be submitted to the authority in charge (within three months in Germany according to BVOT (1998)).

5. PLUGGING DESIGN OF HORSTBERG Z1

For the Horstberg Z1 well, all the designs are done in accordance with the Lower Saxony Deep Drilling Ordinance (BVOT, 1998). Innovative ideas and best practices in the oil and gas industries are considered for three unique designs. The cost of design implementation is the main factor for selecting the preferable design; nevertheless, cement plug effectiveness and the risks associated with setting cement and mechanical plugs are also considered.

A minimum of 50 m cement plug with a mechanical plug is required as a permanent barrier; where no mechanical plug is used, a minimum of 100 m cement plug shall be used as the permanent barrier. No part of the wellbore is to be left void.

Design Plan A (DPA): This design option has the highest number of mechanical plugs. A schematic diagram of the wellbore plugs and abandonment is shown in **Annex 1**.

Design Plan B (DPB): This design is done in accordance with best practices in the oil and gas industry as shown in **Annex 2.** The idea is to reduce the number of round trips to be made in the P&A operation, which is achieved by replacing the use of a mechanical plug as the base for every cement plug with high viscosity mud to create a temporary base for the cement plug. This approach allows the cement slurry to set and form a good cement-to-casing and/or cement-to-formation bond.

Design Plan C (DPC): DPC is a state-of-the-art idea of using a long cement plug across all the perforated sections at a certain depth, from the production casing cutting point back to the final depth, as shown in **Annex 3**. Within this section, the need to fill the intermediate spaces between the cement plugs with mud and the use of mechanical plug is avoided.

Table 2 presents advantages and disadvantages of each design plan.

Table 2 – Comparison of design plans

Plan	Advantages	Disadvantages
Design Plan A **DPA**	Has a combination of mechanical and cement plugs and is considered a better barrier than only using a cement plug, particularly in bigger diameter casings and fresh water zones. This is because of the increased tendency for heavier fluids to swap with the lighter fluids in large diameter casing.	Requires a higher number of round trips compared to DPB. As a mechanical plug is used as the base for every cement plug, DPA requires the longest time of implementation among the three design plans and may yield issues associated with the mechanical plugs installation.
Design Plan B **DPB**	Requires less round trips compared to DPA. It uses highly viscous mud as the base for the cement plug; this makes the plugging process faster than when a mechanical plug is used as the base for the cement plug.	A combination of mechanical and cement plug is considered a better barrier than a cement-only plug that is used in this design plan.
Design Plan C **DPC**	Simple design. Provides a complete seal-off of the wellbore from 4120 m back to 1885m.	Too complex to realize with the current technology, because a 2235 m cement plug cannot be pumped into the wellbore in one run. As the longest cement plug that can be pumped/placed in one run is 300 m, a minimum of 8 runs (times) is required. There is the risk that each run of cement plug will form a separate layer, which may increase the tendency for fluid migration. There is also a high risk of the working string getting stuck in the cement, as the cement may set before the plugging operation is completed.

6. COST ESTIMATION

The basic parameters used for estimating the cost of all the design plans are presented in this section. **Annex 4** shows the equipment rental rates, job and service charges from local companies, used to determine the cost of different activities that are involved in the P&A of the Horstberg Z1 well. Prices are given in local currency (EUR to USD exchange rate = 1.18). A conventional 150 t workover rig is selected by determining the highest hook load that is anticipated to be pulled out of the wellbore.

The service equipment charges and personnel rates used for the cost estimate are the same for all the three design plans. **Table 3** gives a summary of the cost estimate for the three design plans, with DPC having the highest implementation cost of EUR 1.31 million, followed by the DPA with EUR 1.27 million, and the DPB having the minimum implementation cost of EUR 1.08 million.

The total number of days it takes to implement every design plan and the number of cement plugs that are to be set in each design plan have a significant influence on the total cost. It takes approximately 42, 35 and 41 days to implement DPA, DPB and DPC, respectively. The number of cement plugs required to implement DPA, DPB and DPC are 6, 6 and 10, respectively.

Table 3 – Cost summary of all design plans

Activity	Cost of the design plan (EUR)			Comments
	A	B	C	
Rig cost	698,100	589,936	694,332	Rate multiplied by days
Diesel	53,384	45,113	53,096	Rate multiplied by days
Mud engineer	54,400	44,800	54,400	2 shifts/day
Mud cost	57,639	57,284	44,311	Volume (m^3) * cost EUR/m^3
7" Bridge plug/cement retainer	12,000	3,000	0	Number of plugs * cost/plug
9 5/8" Bridge plug/cement retainer	3,000	0	3,000	Number of plugs * cost/plug
13 3/8" Bridge plug/cement retainer	6,000	0	6,000	Number of plugs * cost/plug
Cementation	98,267	91,067	139,653	Depends on the number of cement plugs per design plan
Scraper and operator cost	35,600	29,000	35,600	3 scraper runs
Cutter	21,000	19,700	44,400	2 cutter runs
Spear	43,300	34,200	42,000	3 spear runs
Waste cost	41,291	41,291	41,291	Volume (m^3) * cost (EUR/m^3)
Security	16,426	13,881	16,337	Rate multiplied by days
5 Containers	71,863	60,729	71,475	Number of containers * rate * days
Drill pipe	62,332	52,674	61,995	Rate EUR3.5/joint/day at 4000 m 1 joint = 9.5 m
Total cost	**1,274,602**	**1,082,675**	**1,307,890**	EUR/USD = 1.18

7. DESIGN PLANS COMPARISON

All three design plans are compared in terms of their technical considerations, cost, safety, and ease of implementation.

The basic idea for designing DPA and DPB is the same, as 6 cement plugs of the same length are set at the same depth in the two designs. The difference between DPA and DPB is that in DPA, mechanical plugs are used as the base for every cement plug. In DPB, highly viscous mud is used as a base for setting every cement plug.

Table 4 – Design plan comparison

Component being compared	Design Plan		
	A	B	C
Number of cement plugs	6	6	10
Number of mechanical plugs	6	1	2
Volume of cement slurry + 20% excess (m^3)	43.4	43.4	79.7
Volume of heavy mud + 20% excess (m^3)	164.68	164.68	126.6
Sum of cement slurry and heavy mud (m^3)	208.1	208.1	206.3
Number of round trips	21	16	20

Note: For DPB, heavy mud represents heavy mud + highly viscous mud.

However, 10 cement plugs are required for the DPC, 2 out of the 10 cement plugs have mechanical plugs as their base, while the other 8 cement plugs are non-separated cement plugs. As shown in **Table 4**, design plans A and B have 208.1 m^3 as the sum of cement slurry and heavy mud volume, which is greater than the volume for DPC (206.3 m^3). This is because cement slurry requirements for the perforated sections in DPA and DPB are calculated with a 50% excess due to squeezing, but in DPC, a 20% excess cement slurry for the perforated sections are considered adequate, as also shown in the annexed diagrams. All the design plans meet the standard requirements in the guidelines established within the scope of the deep drilling ordinance (BVOT). Hence, the design plan B, with its minimum accessories to achieve P&A of the Horstberg Z1 well, could be recommended for implementation based on technical, safety, financial, and implementation considerations.

To allow the cost of every component to be better presented in bar chart form (**Figure 3),** the 7" bridge plug/cement retainer, 9 5/8" bridge plug/cement retainer and 13 3/8" bridge plug/cement retainer are combined and represented as a 'Mechanical plug'. In all the three design plans, the rig cost dominates the estimated cost of P&A of the Horstberg Z1 well.

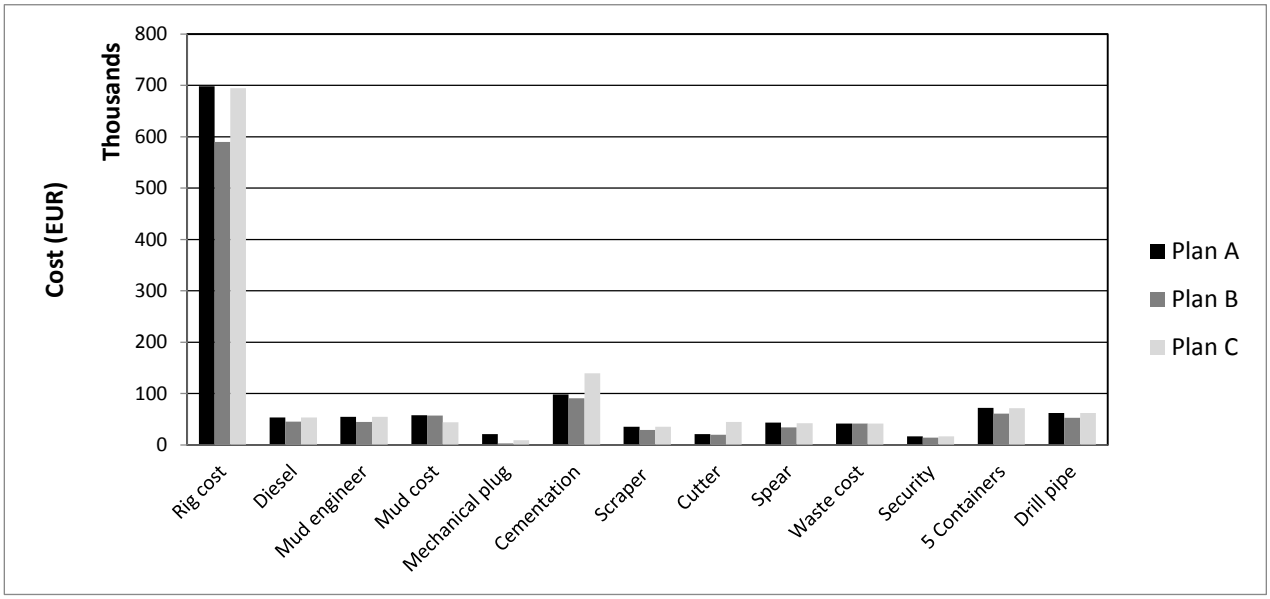


Figure 3 - Cost of equipment and services for P&A in the three design plans

DPA has the highest rig cost of EUR 698 thousand, followed by the DPC with EUR 694 thousand, and the DPB has the lowest rig cost of EUR 590 thousand. The rig cost is directly proportional to the total number of days it takes for implementing each design plan. A reduction in the rig cost will have a significant impact on the total P&A cost of the Horstberg Z1 well. In all the design plans, the second most expensive component is cementation, as shown in **Figure 3**. The volume of cement slurry, number of cement plugs and cementation period for each design plan are the main factors influencing cementation cost.

7.1. SAFETY CONCERNS ASSOCIATED WITH IMPLEMENTATION

One of the risks in P&A operations is stuck pipe, as cement slurry is desired to harden and set quickly to reduce the wait on cement (WOC) period. However, in a situation like in DPC, where a non-separated cement plug of 2235 m is desired, there is a high risk that the first part of the cement slurry will harden before the last part is in place. This could lead to layering and stuck pipe situations. In DPA and DPB, all the lengths of the cement plugs are shorter than 300 m (which is the maximum length of cement plug that can be conveniently placed in the oil and gas industry, based on the current technology). However, special cement retarders could be used to ensure adequate pumping and placement time of the next cement plug, before the previous one will set. Usually, coiled tubing is used for placing long cement plugs by pumping in the slurry and pulling out the tubing simultaneously, but this is not feasible with a 2235 m long cement plug (source: personal communication with staff member of E&P companies). The limitations of coiled tubing in this situation are low pumping rate, high pumping pressure, and the requirement for extensive quality control of the slurry because of anticipated temperature and pressure, safety concerns, and logistics (Regan et al., 2003).

There is also the possibility of a mechanical plug getting stuck in the casing string before reaching the depth at which the plug is planned to be set (SLB, 2015). This is the highest risk in DPA as it has the highest number of mechanical plugs. However, the Horstberg Z1 wellbore trajectory is almost vertical since the average inclination to its final depth is only 4.5°. A vertical wellbore has no tortuous path that can cause unexpected activation of a mechanical plug (Thor et al., 2008), so the risk of a mechanical plug setting unexpectedly has minimum significance on the P&A of the Horstberg Z1 well.

The contamination of the cement plug is relatively low in DPA, as compared to in DPB, since a mechanical plug is used as the base for every cement plug in DPA. In DPB, there is a possibility of the heavy density cement slurry to swap the light density, high viscosity mud, due to the gravity effect, thereby causing contamination of the cement slurry. When cement slurry dilutes/mixes with mud or other foreign matters, the cement slurry setting time increases, the compressive strength development is delayed, and the final compressive strength decreases (Gupta et al., 2014; Ichim et al., 2017). However, this risk can be prevented by taking the following preventive measures:

- Minimal density difference between the cement slurry and mud (George, 2009; Smith et al., 1984; Nelson, 1990) (1.5 and 1.9 SG are recommended for mud and cement slurry respectively (according to personal communication with staff member of E&P companies).
- At least 10 m of high viscosity heavy mud to cover the top of the heavy mud, providing a thick layer that resists shear deformation (source: personal communication with staff member of E&P companies).
- Avoid the use of an open-ended tubing for placement of cement slurry, since it generates high momentum that may break through the high viscosity mud (George, 2009; Smith et al., 1984). A diverter tool at the end of the tubing can be used to change the flow direction of the cement slurry from the vertical downward direction to the horizontal direction (Smith et al., 1984; Nelson, 1990), reducing the momentum of the cement slurry, as the cement slurry hits the casing wall.

A poorly abandoned well is not only an environmental hazard, but also a health and safety threat, as it may provide pathways for formation fluids to migrate up the well to the surface or into shallow drinking water aquifers (IEA, 2009). None of the three design plans have potential to cause cave-in at the surface, because no void space exists in any of the designs.

There is a low risk of inflow of formation fluid into the wellbore or crossflow between different zones in all the design plans for the Horstberg Z1 well as every high-pressure zone or potential high-pressure zone is completely isolated using permanent barriers in both DPA and DPB. Also, in DPC, the section of the wellbore that is connected to the formation is completely plugged with a 2235 m long cement plug. There is a minimum requirement for three cement plugs for abandonment operations (IEA, 2009), which all the design plans satisfy.

The surface casing of the Horstberg Z1 well is fully cemented and its shoe (setting depth) is below the fresh water horizon. In all the design plans, a 100 m cement plug is set above the surface casing shoe to prevent any form of wellbore communication with the fresh water horizon. In DPA and DPC, a mechanical plug is used in addition to the 100 m cement plug. Evidently, the DPB has the lowest protection against possible contamination of the fresh water horizon, yet the 100 m cement plug meets standard requirements in the Lower Saxony guidelines for well P&A.

According to design plans to P&A the Horstberg Z1, the wellbore would be filled with cement slurry and heavy mud, to generate a hydrostatic pressure higher than the formation fluid pressure. This would prevent inflow into the abandoned wellbore. The gel strength of the static mud in abandoned wells reduces slightly over time as the mud dries out. A gel strength of 25 lb/100-sq.ft is recommended for the mud in an abandoned well (Johnson and Knape, 1986; NPC, 2011). Hence, in the event of any inflow into the wellbore. a higher pressure is required to initiate upward movement of fluid in a wellbore column that is filled with heavy mud.

According to Vijn and Fraboulet (2001), it is important that the cement plug has a low bulk shrinkage, low permeability, and is chemically stable in an abandoned well. Mechanical strength is less important since the well is in a static condition. To ensure that the cement plugs overcome these problems in the Horstberg Z1 well abandonment, the cement slurry preparation would consider the following (Vijn and Fraboulet, 2001):

- Fumed silica should be used to increase the chemical resistance.
- Silica flour should be added to reduce the permeability as the bottom hole temperature exceeds 110°C.
- Expansion additive to prevent gas breakthrough and to compensate for shrinkage in pipe-pipe situation must be added as well.

8. CONCLUSIONS

Based on the investigations made in this research work, the rig cost dominates the P&A cost of the Horstberg Z1 well. In the DPA, 54.8% of the total cost is rig related, while rig cost contributions for DPB and DPC are 54.5% and 53.1% of their total costs, respectively. The rig cost is directly proportional to the implementation period of each design plan.

The usage of high viscous mud instead of mechanical plug as the base for setting the cement plugs reduces the implementation period significantly, from 42 days for DPA to 35 days for DPB. Consequently, this reduces the total cost, from EUR 1.27 million for DPA to EUR 1.08 million for DPB, with the base rig rate scenario of EUR 17,000 per day. Both DPA and DPB have a similar design plan.

DPB is considered as the best option because it fulfills all the requirements specified in the Lower Saxony Deep Drilling Guidelines at a relatively lower cost to both DPA and DPC. Based on the analysis made in this paper, a minimum of EUR 1.08 million is required to P&A the Horstberg Z1 well, excluding the well site remediation.

With the current technology in the oil and gas industry, the DPC is too complex to achieve, as the maximum length of a cement plug feasible to be placed in one run is limited to 300 m.

No part of the wellbore in all the design plans is left void. Every section of the wellbore is filled with either cement slurry or heavy mud to generate higher hydrostatic pressure than the formation fluid pressure and to avoid soil subsidence at the surface.

The use of a rigless deployment method for the P&A of the Horstberg Z1 well is not feasible. Only a conventional workover rig and hydraulic workover unit can be used to pull out of hole the heavy 7” casing, 9 5/8” casing and 3 ½” tubing.

9. RECOMMENDATIONS

From the analysis of the results obtained on the P&A of the Horstberg Z1 well, it was observed that the rig cost covered more than 50% of the total cost in all the 3 design plans. Hence, more research work should be carried out to reduce the rig rate and to increase the efficiency of the rig by increasing the rate of running in and out of the hole. Likewise, more attention should be placed on the possibility of rigless application to P&A wells, as this would significantly reduce the total cost. Therefore, research work on using rigless approaches for pulling heavier casing or tubing out of the hole should be the performed.

The P&A design plan of each well should be based on the mechanical history of the well, such that the plan is modified whenever the wellbore configuration is changed. This allows every critical issue to be addressed in the P&A planning, rather than it being done to just satisfy the government regulations, which are minimum guidelines to be fulfilled.

Every cement plug should be tagged at its top, to confirm its position and so establish that the cement plug is at the planned depth.

A scraper should be run to remove every foreign matter on the inside of the casing before setting the cement and mechanical plugs to achieve a good cement-to-casing bond and a good seal between the mechanical plug and the casing.

10. NOMENCLATURE

DPA – DESIGN PLAN A

DPB – DESIGN PLAN B

DPC – DESIGN PLAN C

WOC – WAIT ON CEMENT

P&A – PLUG AND ABANDONMENT

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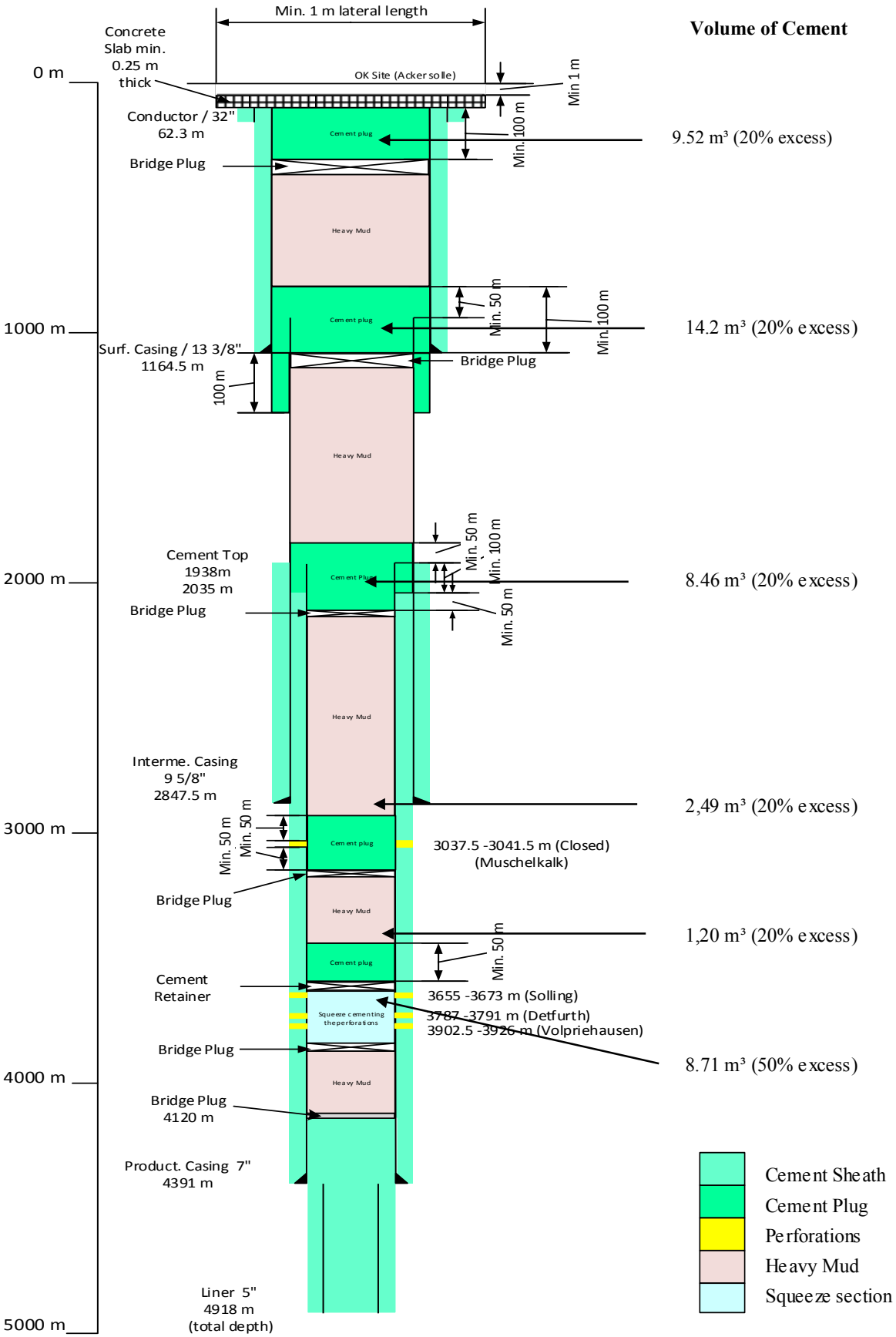
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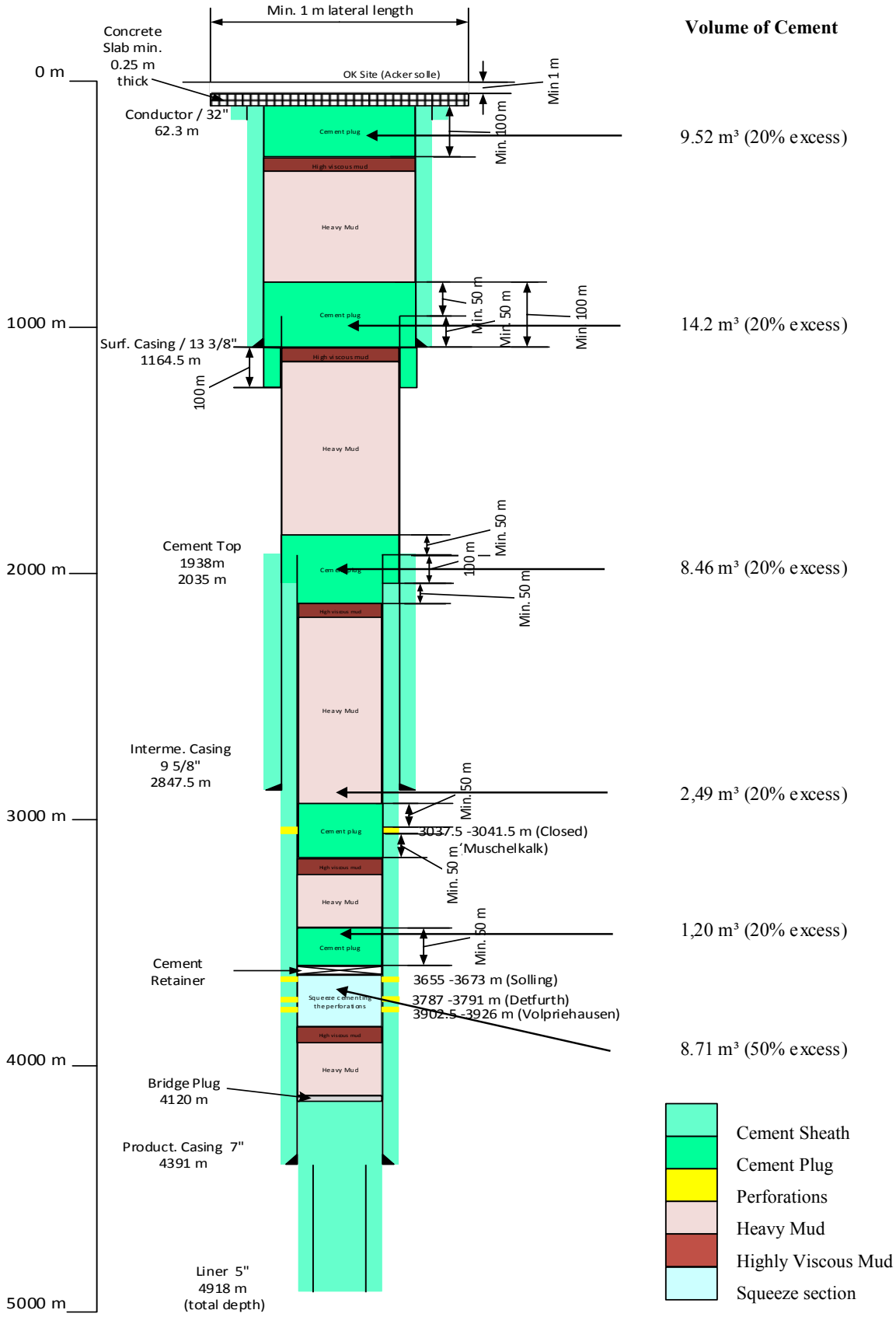
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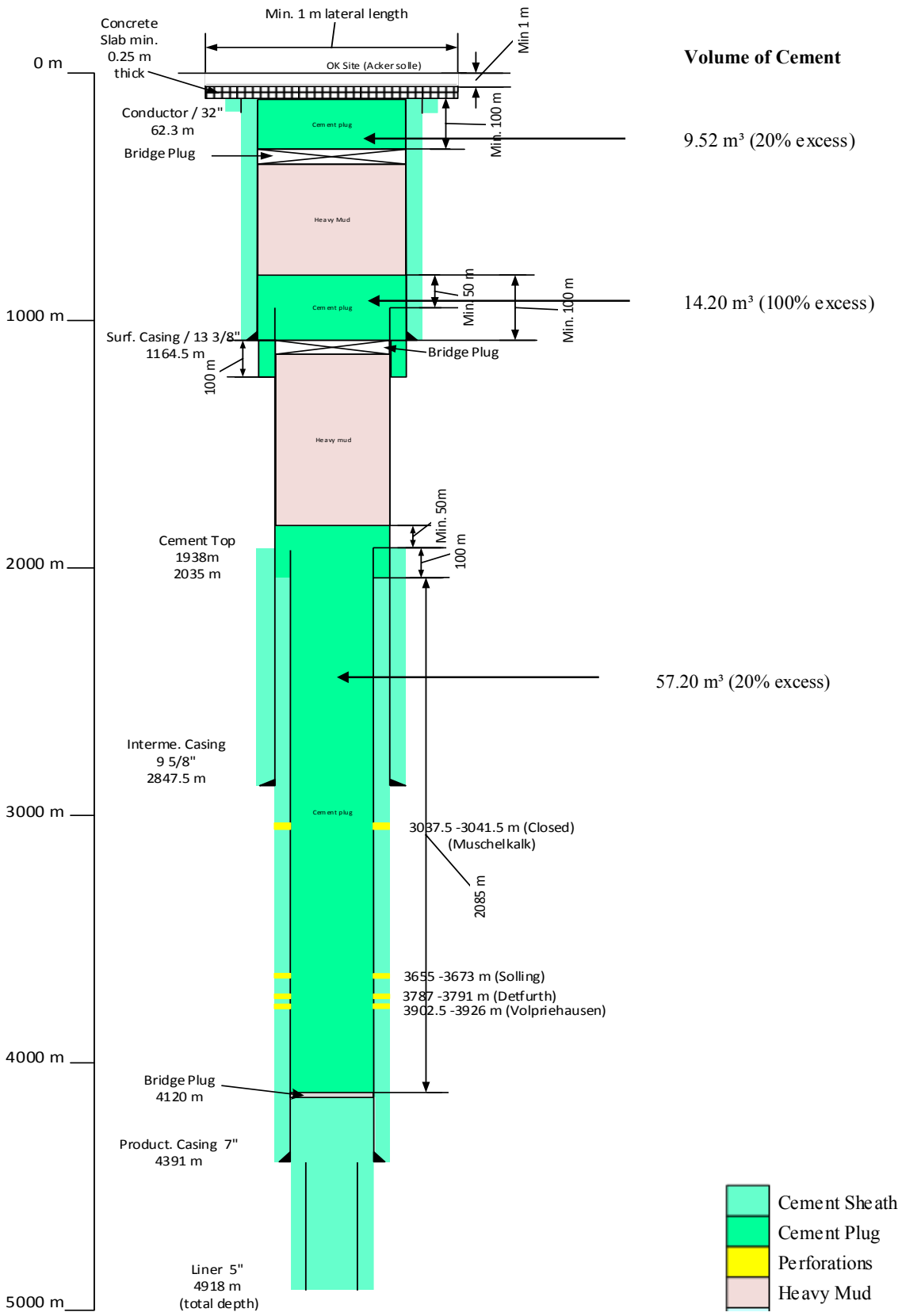
ANNEX 1 – DPA SCHEME



ANNEX 2 – DPB SCHEME



ANNEX 3 – DPC SCHEME



ANNEX 4 - EQUIPMENT RENTAL, JOB AND SERVICE CHARGES

Equipment/Activities	Rate	Unit	Comment
150 tons Rig			
Rig cost	16000 - 18000	EUR/day	
Diesel cost	1300	EUR/day	
Mud engineer			
Rate	800	EUR/day	2 persons
Mud (1.5 SG)	350	EUR/m³	
Bridge plug or cement retainer			
7"	3000	EUR/plug	
9 5/8"	3000	EUR/plug	
13 3/8"	6000	EUR/plug	
Cementation			
Cement slurry (1.9 SG)	550	EUR/m³	
Cement plug	4000	EUR/plug	
Supervisor + operator daily rate	1800	EUR/day	
Approximately 550€/m³ of cement slurry + cement plug job charge (4000 EUR) + supervisor and operator daily rate.			
Scraper/Scratcher run			
Job charge	500	EUR/use	
Daily rate	100	EUR/day	
Operator rate	1000	EUR/day	
Total duration = 1 day before + time for job+ 1 day after			
Cutter			
Job charge	4000	EUR/use	
Daily rate	300	EUR/day	
Operator rate	1000	EUR/day	
Total duration = 1 day before + time for job+ 1 day after			
Spear			
Job charge	1500	EUR/use	
Daily rate	300	EUR/day	
Operator rate	1000	EUR/day	
Total duration = 1day before + time for job+ 1 day after			
Waste treatment			
Waste disposal and treatment cost	200	EUR/m³	
Miscellaneous			
Security	400	EUR/day	
Security (two shifts per day)	200	EUR/shift	
Containers daily rate	350	EUR/day	5 containers
Drill Pipe			
Rate	3.5	EUR/joint	
Maximum depth	4120	m	Well's depth
1 joint	9.5	m	

Note: Information gathered via private communication with E&P companies.



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Estimation of plugging and abandonment costs based on different EU regulations with application to geothermal wells

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