Chair of Drilling and Completion Engineering

Master's Thesis

Development of a Field Ready Design and Data Analysis Technique for Successful Kick-off Plugs

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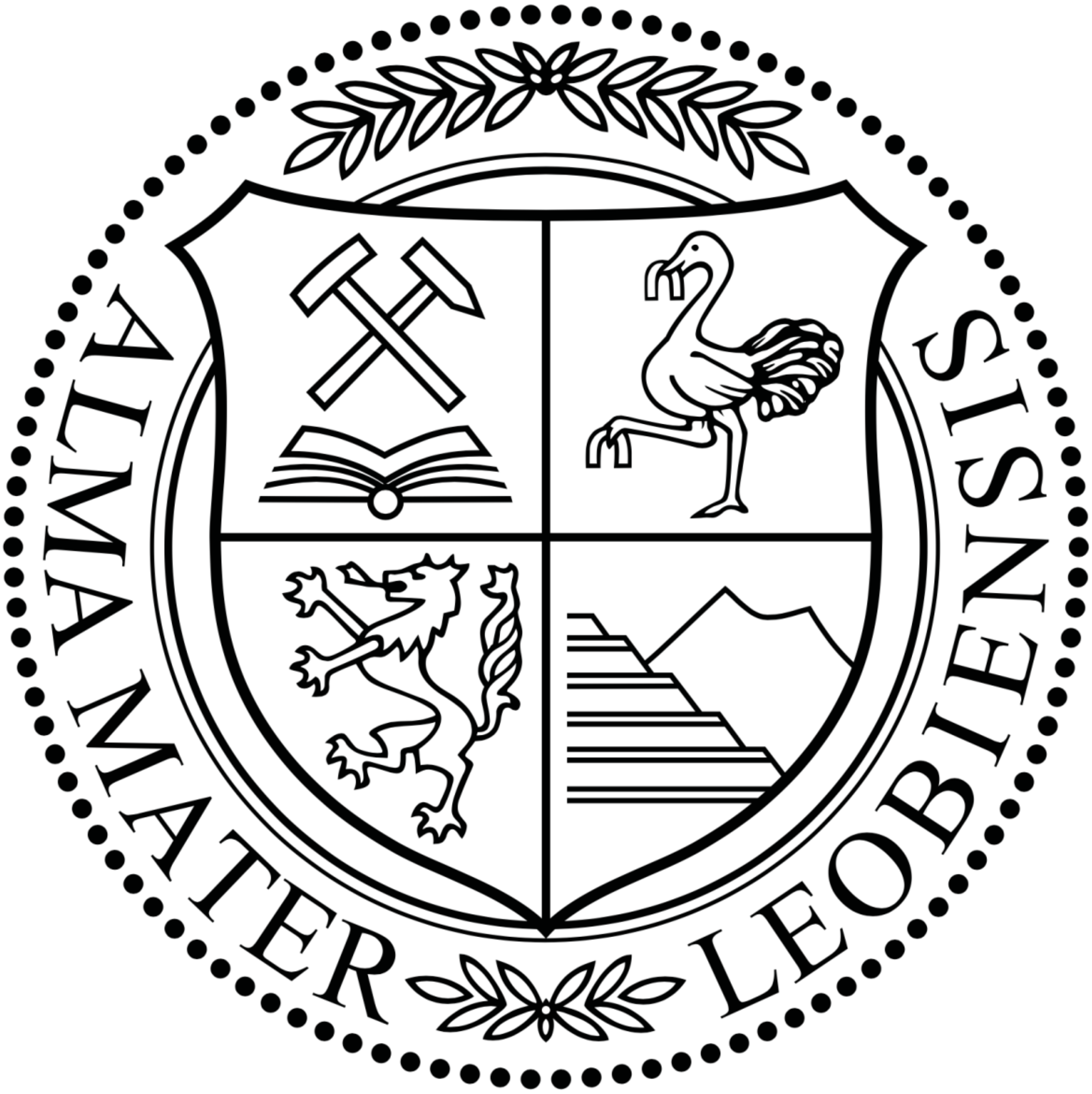
"It's amazing!
More than 7 billion people are living on this planet.
But only a handful of these possess the knowledge and the technology to drill for oil and gas and to make this world go around- every night and every day!"

Emanuel Hofer

"Failure is not an Option!"

Gene Kranz, Aerospace Engineer and Lead Flight Director of Apollo 13, (Title of his Autobiography)

This thesis is dedicated to my parents.
Thank you for your endless support, encouragement and faith.
And to my grandfather Josef who passed away during the completion of this thesis.
I miss you!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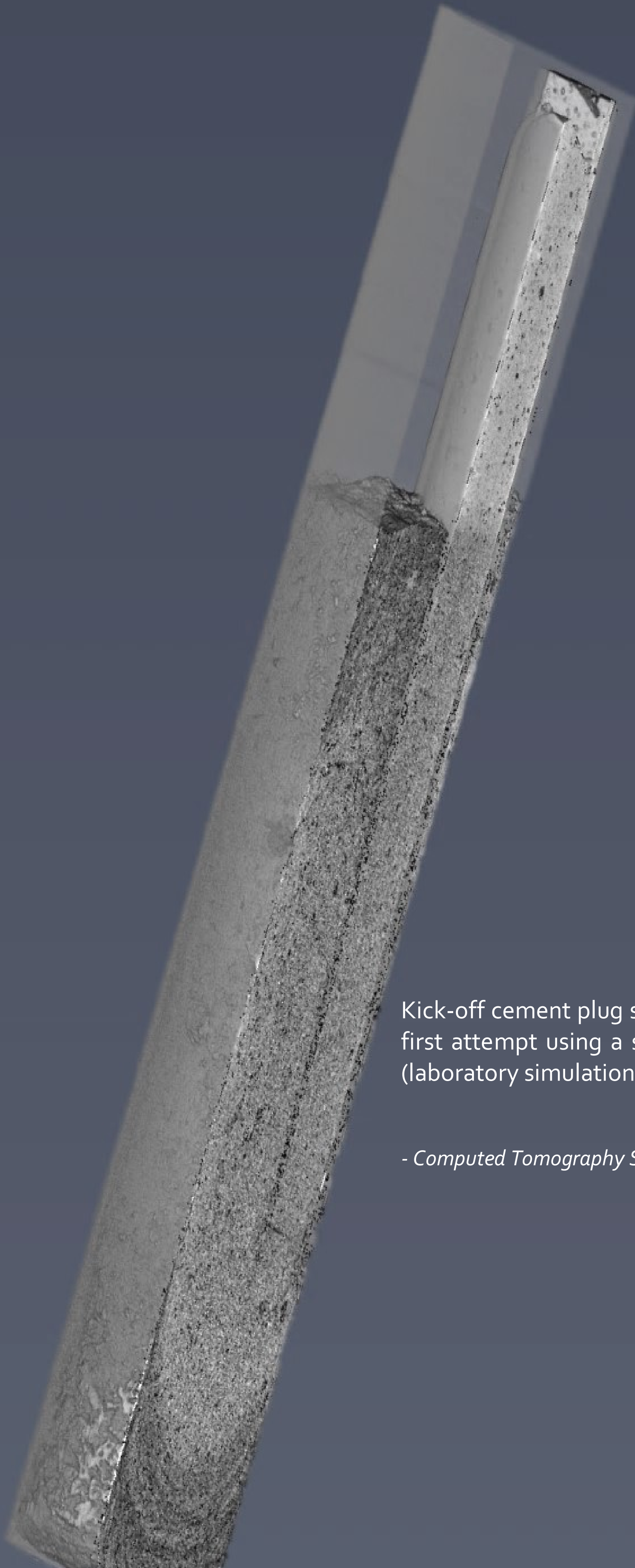

Kick-off cement plug set successfully on the first attempt using a sacrificial stinger pipe (laboratory simulation)

- Computed Tomography Scan (CT) -

Abstract

This thesis covers the methodology of the development of a data analysis tool for designing kick-off plugs as well as laboratory-based simulations and experiments in order to validate the prediction quality.

The data analysis tool can be used to design cement plugs and to simulate the consequence of specific fluid rheological parameters as well as distinctive selected parameters on the outcome of the plug job. The goal of this thesis is the implementation of a simple, field applicable and intuitive program that enables the engineer to design a kick-off plug that fulfils all requirements for a successful placement of the plug on the first attempt.

The thesis describes the development of the data analysis tool starting with a detailed literature review where the most prominent industry related cement plug issues are described in more detail. Based on the assessment, a root cause analysis is implemented that reduces the common plug problems to four distinctive elements. Following the root cause analysis, the development of the design software and its individual modules are explained in detail. All four elements as well as the basic workflow and their structure are illustrated properly. In order to validate the outcome and the prediction quality of the software, laboratory-based simulations are executed. Prior to executing lab simulation runs, they were mathematically simulated using the data analysis tool. Afterwards predicted parameters and observed laboratory results are compared and rated. In addition, computed tomography images (CT scans) support the assessment and enable a direct look into the laboratory produced kick-off plugs. In a last step, a novel compressive strength enhancing material is tested. Therefore, the compressive strength behaviour of a neat Class G cement and fibre reinforced cement cubes are compared and benchmarked.

Recommendations as well as results and future work steps can be found in the appropriate sections as part of the discussion and conclusion chapters at the end of this master thesis.

Zusammenfassung

Die vorliegende Diplomarbeit umfasst die Methodik des Erstellens eines Datenanalyseprogramms für die Konstruktion von Zementbrücken, welche zum Ablenken von Bohrungen verwendet werden, sowie Laborsimulationen und Experimente, welche zur Überprüfung der Vorhersagequalität dienen.

Das entwickelte Datenanalyseprogramm wird für die Planung von Zementbrücken verwendet. Des Weiteren kann man mit dem vorliegenden Tool die Auswirkungen verschiedener fluid-rheologischer Eigenschaften sowie speziell gewählter Parameter auf den Ausgang der Zementationsarbeiten simulieren. Das Ziel der Diplomarbeit ist die Einführung eines einfachen, am Bohrplatz anwendbaren und intuitiven Programms. Das Programm soll zur Planung von Zementbrücken verwendet werden, welche schlussendlich alle erforderlichen Parameter die zur erstmalig- erfolgreichen Ablenkung einer Bohrung benötigt werden, erfüllen.

Die Diplomarbeit umfasst die Entwicklung des Datenanalysetools, beginnend mit einer ausführlichen Literaturrecherche. Die Literaturrecherche beschreibt die in der Erdölindustrie bekanntesten Probleme, welche eine erfolgreiche Ablenkung einer Bohrung mittels Zementbrücke verhindern. Die Literaturrecherche ist Basis für die anschließend durchgeführte Ursachenanalyse, die die oben genannten Probleme auf vier spezielle Elemente vereinfacht. Im Anschluss wird die Entwicklung des Datenanalysetools sowie der Aufbau der einzelnen Module und deren zu Grunde liegenden Strukturen erläutert. Um die Aussagekraft sowie die Vorhersagequalität des erarbeiteten Datentools zu bewerten, werden im Labor durchgeführte Simulationen herangezogen. Alle Durchläufe werden vor der Realisierung im Labor mit dem genannten Tool mittels mathematischer Simulation geplant. Anschließend erfolgt der Vergleich und die Bewertung der mittels Datentool erörterten Aussagen, mit dem im Labor tatsächlich ermittelten Fakten. Zusätzlich erfolgt die Bewertung mittels CT-Scans, welche einen direkten Blick in das Innere der im Labor erstellten Zementbrücken ermöglicht. Im letzten Abschnitt der vorliegenden Diplomarbeit wird ein neuartiges Additiv vorgestellt und getestet. Das Additiv soll die Druckbelastbarkeit des Zements erhöhen. Hierzu wird die Druckfestigkeit von purem Zement der Güteklasse G mit Fasern verstärktem Zement verglichen und bewertet.

Empfehlungen sowie einzelne Resultate und zukünftige Arbeitsschritte werden in den entsprechenden Abschnitten der Kapitel „Discussion“ und „Conclusion“ am Ende der Diplomarbeit näher erläutert.

Acknowledgements

I would like to reward my gratitude to my supervisor and mentor at the Mining University of Leoben, Univ.-Prof. MBA PhD Ravi Krishna for his support, guidance and assistance during my studies and during the completion of this thesis. I am truly thankful for your help!

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Special thanks to the Chair of Reservoir Engineering and Dipl.-Ing. Pit Arnold for his support during the CT measurements.

My family deserves special acknowledgement for all their patience, inspiration and help throughout the entire duration of my study. I appreciate your endurance, implicitness and your relinquishment to facilitate the completion of my academic dreams.

Thank you all!

Glück Auf!

Contents

Chapter 1 Introduction

"I, Erle P. Halliburton [...] have invented a certain new and useful Improvement in Methods and Means for Cementing Oil-Wells."

This sentence is the introduction to Erle Halliburton's patent specification "Method and Means for Cementing Oil-Wells" awarded on March 1^{st}, 1921. With his new invention E. Halliburton not only founded his service company "Halliburton Oil Well Cementing Company" but also invented cement as a new and versatile component of each oil well. Figure 1 shows the patent drawing of Halliburton's invention.

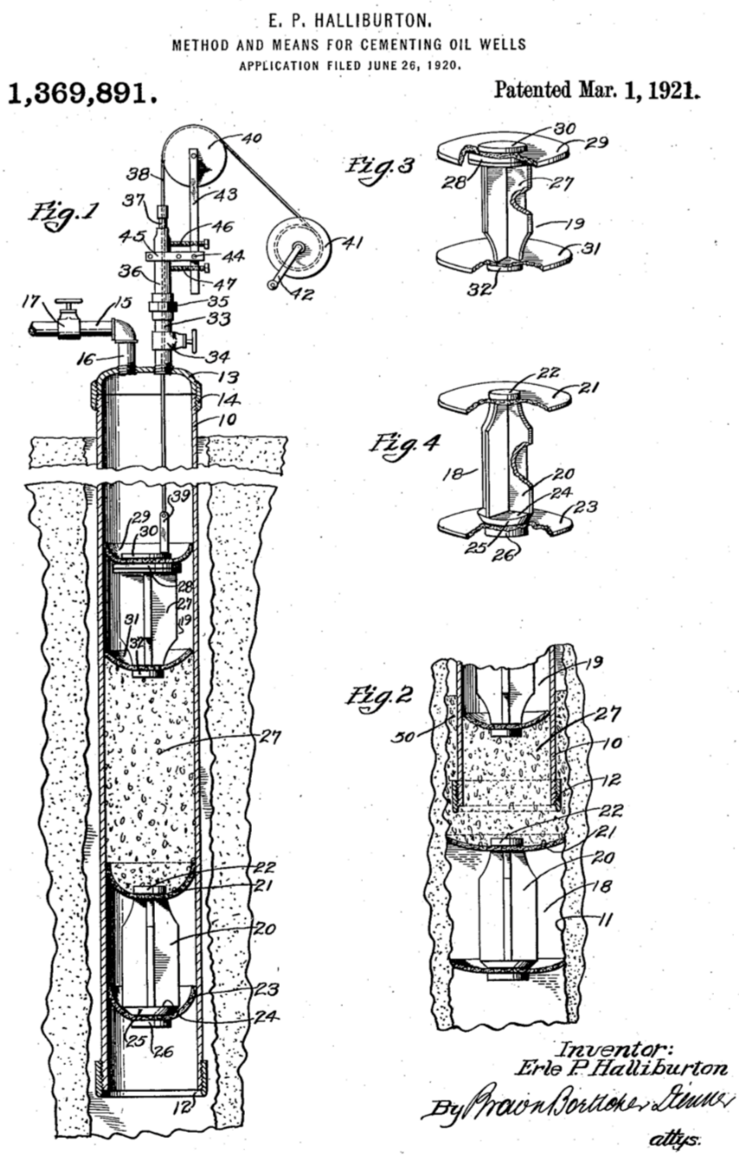


Figure 1: E.P. Halliburton's patent drawing "Method and Means for Cementing Oil-Wells".

Halliburton was one of the first who used cement during oil well drilling in order to set casings safely in place. The idea of using cement as an oil well construction additive is as revolutionary as simple and genius. Cement is cheap, easy to handle and available on nearly every place of the world, regardless where the well is drilled. Cement is stable, establishes a bonding between both, the casing steel and the formation and can be used in a wide range of downhole environments. In the meanwhile, cement is used for many applications. Beside the save installation of casings and liner pipes, cement is also used as a lost circulation material, for temporarily or permanent well abandoning, used to protect weak formations during well testing or as a kick-off base for sidetracking wellbores. The variety of cement application is large and in principle engineers are still using the same technology as nearly 100 years before, when Halliburton invented his way of making oil well drilling safer. The main difference between oil and gas exploration these days and at the time when Halliburton invented his system is, that the circumstances have changed completely. Halliburton made his research and experiments in oilfields of shallow depth, with boreholes of simple trajectory and manageable ambient temperatures. Cement enforced to be the optimal sealing technology for those wells. Production could be enhanced on a large scale and safety was improved massively. Nowadays, the days of simple oil well drilling are gone. Modern petroleum companies are forced to explore in remote and deep offshore areas, drill complex deviated multilateral wells or struggle with extreme downhole pressures and temperatures. The industry uses a wide range of the old inventions today, without or with only insufficient improvement leading to unsuccessful completion of cementing jobs.

In deep-water and ultra-deep-water areas, cement and cement plug jobs can be very challenging. Small drilling windows, lost circulation problems as well as high pressures and high temperatures may lead to a failure of the job. Cement plugs, that are not set on the first attempt, lead to in massive Non-Productive Time (NPT) and Lost Time (LT) issues. A study conducted by Bogaerts et al. (2012) shows, that more than 53% of deep-water cementing jobs are cementing plug operations. The majority of those plugs are set for abandonment reasons, but also kick off, lost circulation and squeeze operations. The assessment shows that the planning phase for primary cementing jobs (cementing the casing in place, after the section was drilled) receives more attention compared to the design of cement plug operations. Operators spend only little time on planning cement plugs, but investigations show that already the change of small parameters decide about success or failure of the operation. Plug jobs should not be standardized but adapted to the circumstances that are present in the wellbore.

There is a difference if the plug is landed in a cased hole or open hole section. Open hole sections often prevent the safe installation of bridge plugs as a cement base. Such wellbores require a viscous and dense base fluid that provides a sufficient interface stability in order to land a cement slurry on it. A cement plug that is set in an inclined wellbore suffers from different issues than a plug that is used to e.g. sidetrack a simple vertical well. In a vertical section, the density difference between the base fluid and the slurry is crucial. Cement plug design parameters for deviated wells are different. Here, improved viscosity and yield characteristics of the base fluid and the cement slurry promote the success rate.

The following thesis focuses on industry related problems and possible solutions for kick-off plugs. Kick-off plugs are used as a base to sidetrack a wellbore. The reasons for sidetracking a wellbore can be versatile but often operators have to overcome an obstacle like a fish (lost tool or part of the drillstring in the wellbore) or to unlock new reservoir horizons from existing wellbores. To do so, a cement plug is set at a designated depth of the well. The cured plug provides a base and should guide the drill bit away from the existing well into the formation. This happens only if the compressive strength of the cement is higher compared to the strength of the lithology. If this is not the case, the bit will drill the cement plug and the operation must be repeated. Theoretically a well can be sidetracked on the first attempt if all design parameters are chosen carefully. Research has shown that in real life such plugs very often fail which results in additional effort and costs.

The thesis covers a detailed literature review that focuses on the different types of cement plugs (abandonment plugs, lost circulation plugs, isolating plugs or kick-off plugs) as well as the individual cement placement methods. Furthermore, characteristics and compositions of oil well cements as well as hydration processes, API norms and their classifications are listed in more detail. Following the literature review, a root cause analysis delineates the most important industry related challenges for kick-off plugs. The chapter covers an itemized research about the most important plug issues and describes particular procedures that lead to plug failures. For the failure investigation, 35 different papers as well as pertinent literature are analyzed and rated. The failure analysis provides the foundation for the root cause assessment.

Based on the findings of the assessment, a kick-off plug design software is developed. The program calculates the four most important design parameters in order to produce a successful cement plug. To evaluate and verify the prediction quality of the software subsequent laboratory-based simulations are conducted. The experimental set-up consists of a mini drill rig, including a manifold, hoses, pits and a pump which represent the necessary surface equipment, as well as a borehole and a drillpipe/stinger system which simulate the downhole and subsurface installations of a real well. The tools and workflows are described in more detail in the corresponding chapters. To conduct the experiments, a cement plug is first designed with the software. Afterwards all relevant rheological as well as technical input parameters are developed in the laboratory. If the laboratory assessed variables (fluid density, viscosity and yield) match with the theoretical specifications of the program, the actual experiment is performed. Afterwards the outcome of the experiment is compared with the prediction of the software. In a last chapter an alternative material for improving the compressive strength of an oil well cement is described. The enhancement of the cement's strength is tested and confirmed with laboratory tests. The tests as well as the outcomes are described in the subsequent passages. The thesis is finalized by a discussion including the most important results as well as a detailed concluding chapter.

Chapter 2 The Necessity of Setting Cement Plugs

2.1 What are Cement Plugs

Cement plugs are an essential but, in most operations underestimated and disregarded component of nearly every modern oil and gas well. Cement plug operations as well as squeezing jobs are allocated to the so called "secondary cementing" or "remedial cementing" technology, whereas all other commercial cementing operations e.g. cementing a casing in place, are associated as "primary cementing" technique (**Figure 2**).

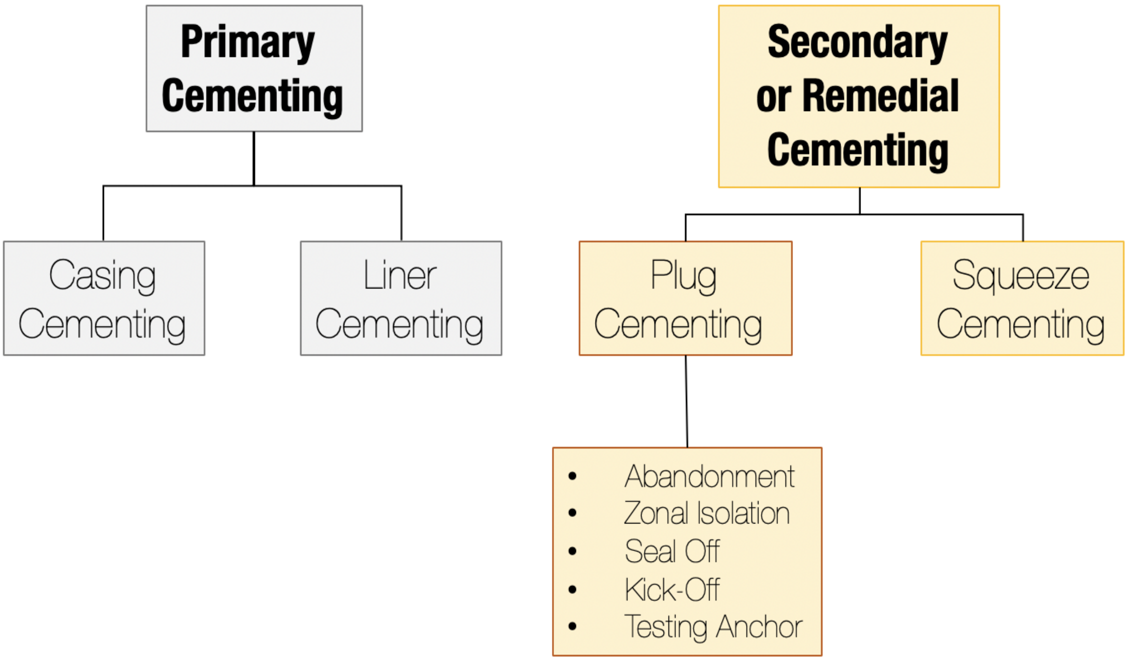


Figure 2: Distinction between Primary and Secondary Cementing Technologies

Cement plugs are set in the casing or in the open hole section of the wellbore and should prevent fluid movement, either temporarily or permanently- if set correctly. Furthermore, cement plugs can also provide a departure point for directional drilling operations or act as an isolating bulkhead in fighting lost circulation zones. The key reasons, why the petroleum industry uses cement plugs are listed below and will be explained in greater detail in the section 2.3:

- **Permanent abandonment of a well** (according to governmental regulations either if a dry hole was drilled or production has dropped to a critical and uneconomic point)
- **Temporary abandonment of a well** (for re-entry if e.g. the oil price is too low and production would be uneconomic or an exploration well has been drilled successfully and future hydrocarbon yield has to be planned)

- **Abandonment and isolation of a depleted hydrocarbon zone**
- **Isolation of a damaging fluid** (isolates zones containing damaging fluids from hydrocarbon bearing formations)
- **Seal off Lost Circulation (LC) zones** (in case of severe fluid losses, cement plugs can be set to seal off the high porous and/or fractured lost circulation zone from the wellbore, by squeezing the slurry into the cavities of the formation, initiating at the same time a bridging effect)
- **Provide a seat for directional drilling and side tracking** (in some cases directional drilling or side tracking cannot be performed without problems e.g. a fish or part of a pipe blocks the potential drill path. For this purpose, a cement plug, so called whipstock, can be set which provides a seat and new departure point for further deviated drilling operations)
- **Isolate a zone for formation testing** (the cement plug or test anchor isolates the zone of interest and submits a tight and durable bottom for the test)
- **Fixing of casing and tubing leaks**

The cement plug itself is a pre-calculated volume of cement slurry that is placed at the desired depth of the wellbore. In contrast to the primary cementing technologies, cement plugs can be set in the cased hole of the well or in the open hole section, either temporarily or permanently. Before the remedial cementing job can be executed, the well has to be prepared in the forefront. Under certain circumstances, more precisely if the plug has to be set off-bottom, there is the chance that the cement may fall down the wellbore due to gravitational forces. For this reason, a different plug has to be set below the actual planned cement operation. This plug can be either a mechanical one (bride plug) or a reactive or viscous fluid, where the density of the fluid is according to Nelson and Guillot (2006), prepared to be halfway between the wellbore fluid and the density of the desired cement slurry (Figure 3-a). After preparation is completed, the slurry is mixed at the surface and pumped down the borehole. Normally the cement is pumped via drillpipe or coiled tubing until all prepared volume is placed at the desired depth (Figure 3-b). Afterwards, the pipes have to be removed but rarely also some parts are left back in the hole. (Nelson and Guillot 2006).

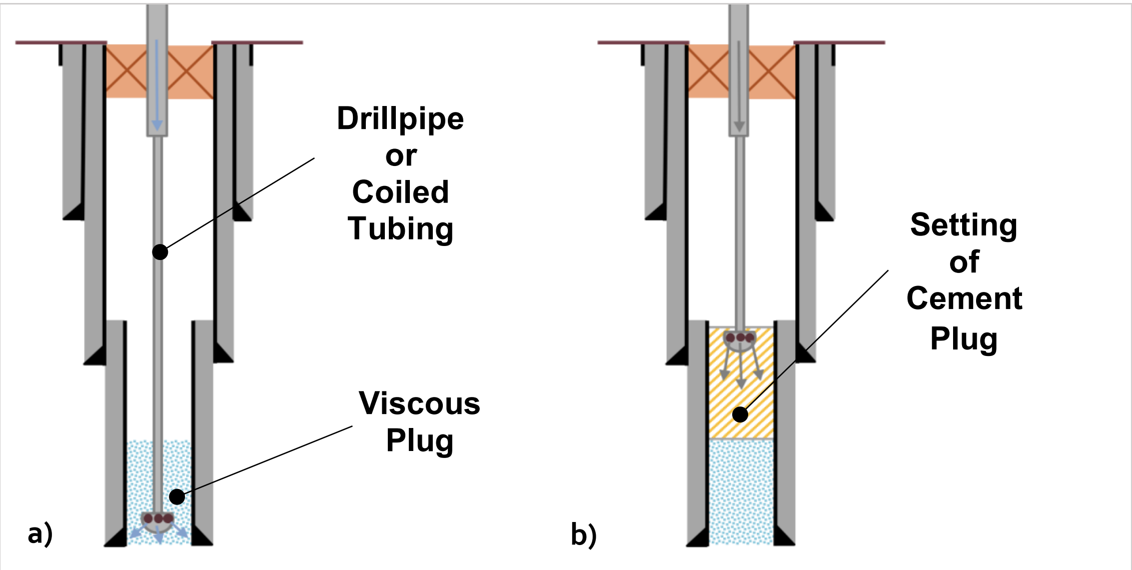


Figure 3: Remedial cementing (Plug cementing) operation steps
cf. Nelson and Guillot (2006)

Correct planning, designing and proper setting of cement plugs is of high importance to ensure an accurate sealing of the wellbore. The integrity of the respective plugs should always be verified but various parameters such as downhole temperature, cement slurry design, wellbore trajectory, mud contamination and other issues discussed in subsequent chapters, may lead to an impractical and flawed cement plug operation. Especially when reservoir horizons or entire wellbores are depleted and have to be plugged permanently, cement plugs as the primary bore barrier, should allocate 100% sealing capacity. If the abandonment is not executed correctly, groundwater horizons may be contaminated by hydrocarbons or surface leaks that lead to massive environmental issues.

For this purpose, several industry related standards were implemented to ensure that oil and gas companies execute plugging jobs according to the rules and state of the art. One of these standards are the so called "NORSOK standards" processed by the Norwegian Petroleum Industry. The standards are very strict, ensure highest level of topicality and represent a worldwide benchmark regarding safety, requirements and technical feasibility and are discussed in the following chapter in more detail.

2.2 Regulations for Cement Plug Jobs- The NORSOK Standard D-010

According to the Standard Norge's website, the NORSOK standards *"are developed [...] to ensure adequate safety, value adding and cost effectiveness for petroleum industry developments and operations. Furthermore, NORSOK standards are as far as possible intended to replace oil company specification and serve as references in the authorities regulations."* (Standard Norge 2018).

The rulebook itself consists of several NORSOK standards, where all of them have to be executed and followed by every petroleum company that operates its business in Norway. Initially the standards were established to unify general regulations and increase safety in the oil and gas business in Norway. Nowadays, many of the standards have become an industry benchmark and are applied by a wide range of petroleum companies and administrations all over the world. This and the fact that the NORSOK regulations are one of the strictest, safest and technically sophisticated ones, are reasons why a subchapter is dedicated to them in this thesis.

One of these standards, the NORSOK D-010 also covers cement plugs, more specifically plugging and abandoning (P&A) of depleted petroleum wells. Most of the cement plug jobs are P&A of wells, either temporarily or permanently. Since abandonment plugging is on the one hand a cost intensive and a time-consuming matter, but on the other hand have to create a fluid tight and absolute impermeable barrier and have to last for many decades it is even more important to perform it on a safe matter and follow strict rules. Chapter 9 of this regulation describes the norms and standards which should be fulfilled, if a well is being plugged.

According to the regulation D-010, chapter 9 (NORSOK standard 2013) three different types of plugging techniques are covered:

- Temporary suspension
- Temporary or permanent abandonment of entire well
- Temporary or permanent abandonment of a segment of a well (e.g. for side tracking)

If a well is *temporary suspended*, production or injection is cut for a limited period of time. The X-mas Tree (XT) is installed on site and well control equipment is not removed in order to monitor the behaviour of the borehole at any time. According to the above stated regulation, the well barriers (WB) (primary and secondary) and their corresponding well barrier element (WBE) (e.g. casing, cement, BOP) materials should withstand all conditions that occur during the suspension, including contingency. Only in this case, wellbore related fluids or temporary mechanical plugs act as a time limited barrier. Cement plugs must not be set at this type of condition.

According to the regulation D-010, a *temporary abandonment* (TA) means that the well is plugged for a period of time but there is always the possibility of re-entering the wellbore. The plug should be retrievable or drillable in this case and XT and Blow-out Preventer (BOP) are removed. The selected WBE material should withstand all conditions that may occur during a timeframe twice the temporary abandonment duration. Cement plugs act as the major and primary WBE to prevent unwanted fluid flow. Furthermore, a permanent monitoring of the annuli and tubing pressure should be possible and if the well is located subsea and planned to be plugged for more than one year, a monitoring and observation plan should be permuted.

If the hydrocarbon reserves are depleted or production becomes uneconomic, oil and gas wells have to be abandoned in a way, that fluid flow is prohibited eternally. Such *permanent abandonment* (PA) follows more strict rules compared to the above described operations, since improper setting of abandonment plugs can cause environmental damage over decades. NORSOK D-010 suggests here the installation of primary and secondary WB. Primary WB act as the first line of defence against unwanted fluid flow. To provide a backup for the first line, a second WB should be assembled. The WBE of the primary WB is always a cement plug, whereas the second WBE could be a cement plug or a mechanical one. In addition to the already described WBE a third WBE, the so called "Open Hole to Surface Well Barrier Element" (OHWBE) has to be installed in the surface region of the bore. The purpose of this WBE is to isolate flow paths permanently from exposed formations to the surface after casing was cut and retrieved. The length of this WBE has to be sufficient to guarantee full protection and isolation of exposed formations. The plugs have to be realized in a way, that the complete cross section of the wellbore is sealed, including all annuli to prevent vertical and horizontal fluid movement eternally. Figure 4 represents a wellbore that is permanently abandoned, according to the NORSOK D-010 regulations. The surface and intermediate sections were cased and cemented up to the top, whereas the production interval was completed by a liner. Following the rules, three plugs have to be installed to avoid future fluid flow. Further details and information are described in Figure 4.

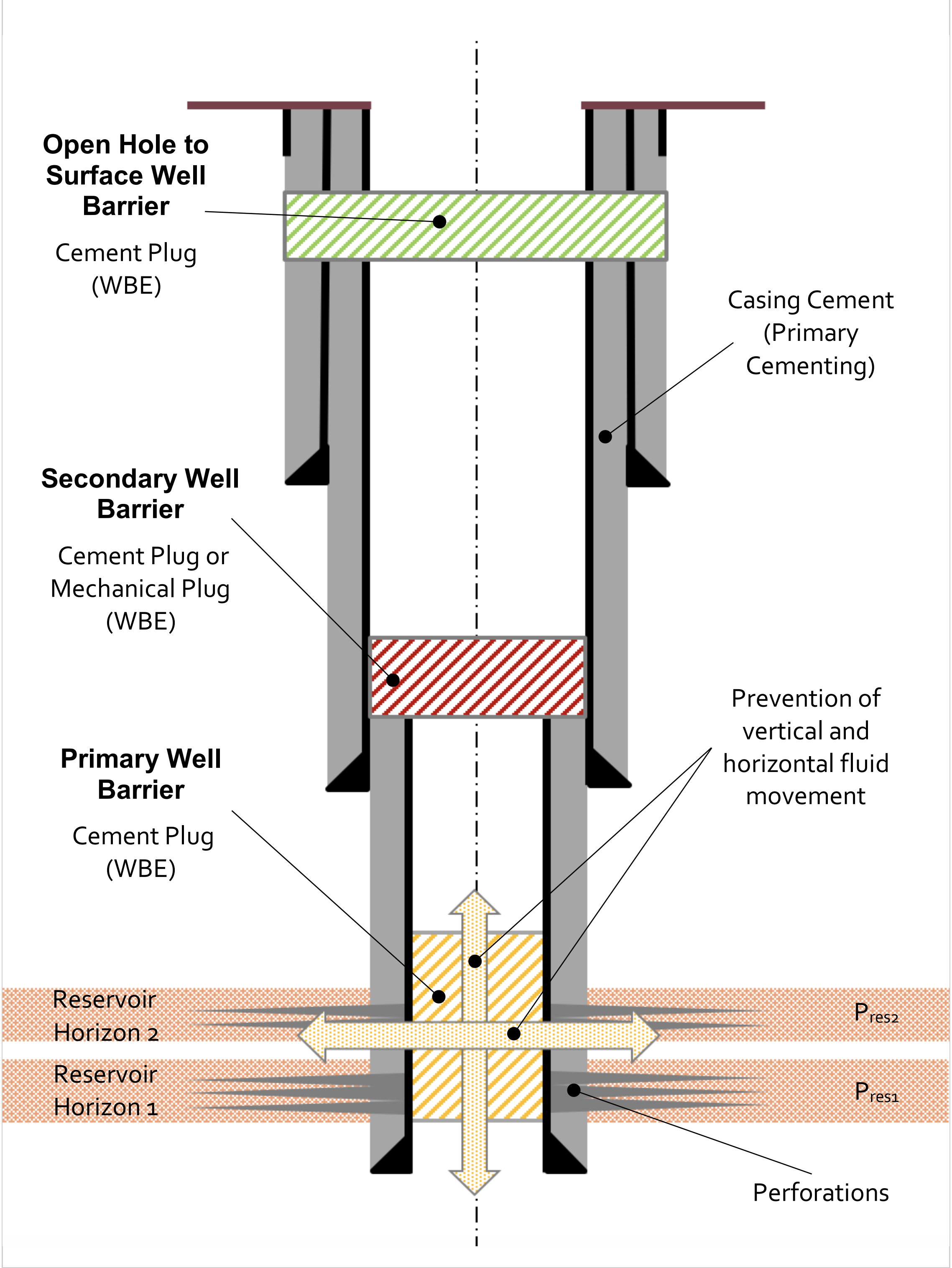


Figure 4: Illustration of a permanent abandoned well, acc. to the NORSOK D-010 regulations.

The yellow cement plug represents the primary WBE. As defined in the regulations, the primary WBE has to be set across and above the perforations of the wellbore. When different or multiple reservoir horizons are located within the same pressure regime ($P_{res1} = P_{res2}$) the horizons can be seen as one unit and the primary WBE has to be set across all perforations. In addition, also a secondary WBE (red plug) has to be installed, ideally across the liner plug segment. The OHWBE (green plug) has to be set in the surface region after casing was cut and retrieved to protect the environment; cf. NORSOK D-010 June 2013

As the example in Figure 4 states, the placement of the plugs needed to abandon a well permanently are very strict. Not only the number of plugs but also the minimum length required, the type of plug and plug characteristics are prescribed by the NORSOK D-010. The cement plugs have to be executed in a way, that if the primary WBE fails, the second WBE is able to withstand all potential pressure build up scenarios.

Corresponding to the regulations D-010, permanent WBE should have the following demands:

- Provide a long-term integrity- ideally eternally
- Impermeable (fluid tight)
- No shrinking features
- Should be able to withstand mechanical loads and impacts
- Resistant to miscellaneous gases such as CO_2, H_2S or other corrosive fluids like hydrocarbons
- Wetting characteristic to facilitate bonding to the steel
- Maintain integrity of steel of the tubulars

The general regulation is, that at least one WBE has to be set between a formation with normal or less pressure and the surface and a minimum set of two WBE between a reservoir, containing hydrocarbons or formations with potentials to flow and the surface. The minimum required length of the cement plugs as a permanent WBE are stated in Table 1.

Open Hole Cement Plug	Transition from OH to CH	Cased Hole Cement Plug	OHWBE
100 m MD (50 m MD minimum overlap above a potential inflow point)	min. of 50 m MD extended below the casing shoe	100 m MD (50 m MD if mechanical plug as foundation)	100 m MD (50 m MD if mechanical plug as foundation)

Table 1: Minimum cement plug length required by NORSOK D-010 regulation

Beside the cement plug integrity, operators also have to make sure that the casing cement seals properly. For this purpose, investigations must be done in order to proof the integrity of this WBE. According to the regulation, a cement is designated as a permanent external barrier element if a verification via logging was conducted and the logging results showed a minimum of 30 m of cumulative interval with adequate cement bonding. Subsequent, the internal barrier element (cement plug) has to be set across all annuli at the section of verified integrity of the external WBE. Steel tubulars are not classified as a permanent WBE unless they are supported by cement. Sealing devices containing elastomers are also not declared to be a permanent WBE. Further regulations, requirements and technologies for e.g. different completion types can be extracted from the respective NORSOK standard paper “Well integrity in drilling and well operations”.

The NORSOK standard is one rulebook among many different ones, each investigated by the respective country or company. Every rulebook has its advantages and disadvantages, but the NORSOK standard is a technical sophisticated, deliberated and frequently updated one and therefore screened and treated in this thesis as a representative guideline for well plugging. However, the outcome of every cement plug job will be diminished, if the rules are not followed correctly by the operator and insufficient planning, well preparation and improper plug design precede the operation. Hence, it is important to study the characteristics of the designated wellbore carefully in the forefront and incorporate all relevant parameters affecting cement integrity, to set a tight and undamaged plug successfully at the first attempt.

2.3 Types of Cement Plugs

As already mentioned in section 2.1, a lot of reasons and occurrences require cement plug operations. Either for well control issues if massive losses interfere a safe drilling operation, as a base for sidetracking a wellbore or if the well has to be abandoned to create a long-term seal. Cement plugs emphasize often to be the only practical solution to solve the problems. If the root causes for the issues are known and diverse parameters are included during planning phase, following problems can be solved with cement plug operations:

- Permanent abandonment of a well
- Temporary abandonment of a well
- Abandonment and isolation of a depleted hydrocarbon zone
- Isolation of a damaging zone
- Seal off Lost Circulation (LC) zones
- Provide a seat for directional drilling and side tracking
- Isolate a zone for formation testing
- Fixing of casing or tubing leaks

In the following, the problems will be discussed in more detail to give an overview about the root causes and the types of cement plugs that can be set to solve the issues successfully.

2.3.1 Permanent abandonment of a well

According to the NORSOK regulatory, permanent abandonment (PA) is referred as the state of the well, where the borehole is permanently plugged, all expendable downhole equipment removed and no re-entry or future use planned. PA is one of the main application areas, where cement plugs have to be set. It is a milestone in every life of a petroleum well and normally realized if the production becomes uneconomic over time. Additionally, if a well is drilled but the encountered hydrocarbon quantity is too low for an economic production, the bore is classified as a dry hole and has to be plugged and abandoned by a cement plug combination too.

Regulations for permanent abandonment are very strict and normally ruled by the local government (e.g. NORSOK standard). Oil and gas companies have to follow a certain rulebook, which implies e.g. the type of completion and the appropriate numbers, locations and length of plugs that have to be set.

A detailed description of such a standard and the way how the standard has to be executed can be found in section 2.2.

The main objective of permanent abandonment of a well is, to create an array of impermeable plugs, that hinder unwanted fluid flow eternally. The correct placement, design and verification of the plugs as the internal WBE but also the examination of the casing and liner cement integrity as the external WBE is essential for future environmental protection. According to Nelson and Guillot (2006), permanent abandonment of a well has to be executed in a way to prevent interzonal communication and fluid migration that may contaminate underground freshwater aquifers.

To prevent future hydrocarbon migration, permanent well barriers have the requirements to include all annuli of the bore, meaning that the plugs are set in a way that they extend to the full cross section of the well. This can be either achieved by setting the plug across a verified length of undamaged casing cement (the net length of intact cement that is required is defined by the local authorities) (Figure 5a) or by removing sections of casings, so that the plug can be set from "rock-to rock" (Figure 5b). Anyhow, the plugs have to be designed to seal vertically and horizontally (Abshire et al. 2012)

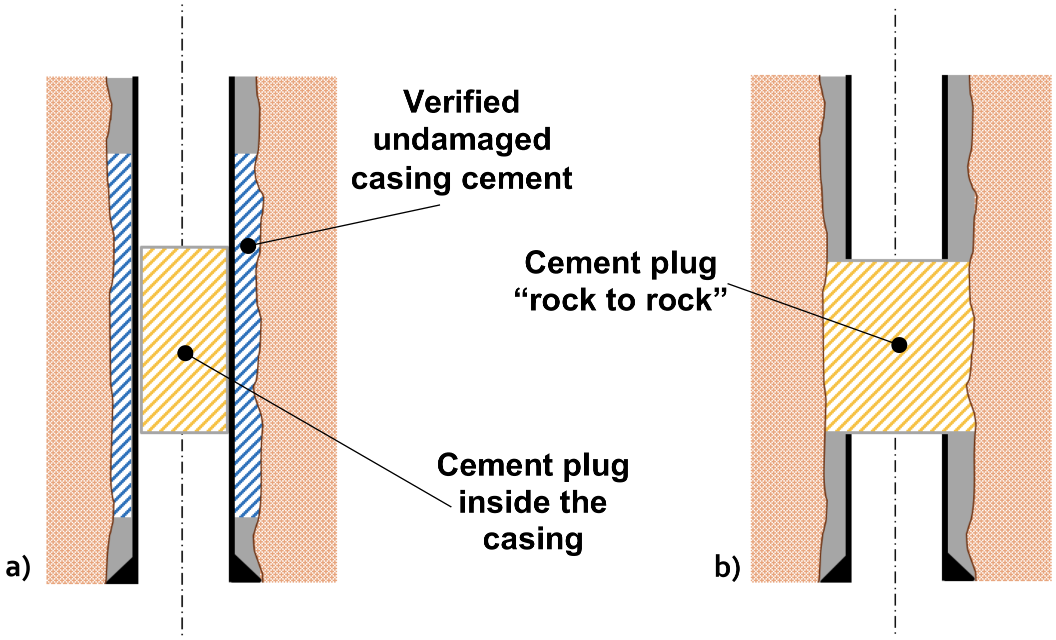


Figure 5: Types of permanent cement plugs

Figure 5a represents a permanent abandonment of a wellbore, where the cement plug (yellow) is set across a verified interval of undamaged casing cement (blue). The verification can be executed e.g. via logging.

Figure 5b represents a permanent abandonment of a wellbore, where a part of the casing was cut and retrieved. Afterwards a cement plug (yellow) was set across the cut section, creating a vertical and horizontal "rock- to rock" seal.

2.3.2 Temporary abandonment of a well

According to the American Petroleum Institute (API), the temporary abandonment of a petroleum well is defined as the status of the well, where the operator plans future utilization of the bore such as e.g. the implementation of Enhanced Oil Recovery (EOR) technology or further exploration activities. The well must be plugged in a way, that workover operations can restore the well's activity at any time. (American Petroleum Institute 2009)

There are various reasons for abandoning a well temporarily, such as lack of technological knowledge (no ability to recover hydrocarbons yet), economic factors (low oil price), preparation for further activities (EOR, fracking or multilateral drilling), miscellaneous delays (crisis, war) and so on. Anyway, the regulation for environmental protection are as strict as in a PA case, but with the difference that temporary plugs should be drillable or retrievable and various safety and surveillance installations are left in the bore.

2.3.3 Abandonment and isolation of a depleted hydrocarbon zone

Stratigraphic and structural conditions often form reservoirs, that contain multiple horizons where hydrocarbons can be expelled from. Hossain and Al-Majed (2015) denote an exploitation from such reservoirs as "Sequential Zonal Production", where completion engineers often decide to use a single string- or single zone completion, although concurrent production would be possible. The decision for a single zone completion is often dedicated to reservoir specifics, safety issues as well as economical and operational reasons and simplifies future well planning. Production starts from the lower most reservoir horizon to bottom up, where depleted formations are temporarily suspended or abandoned by e.g. cement plugs. When the isolation of the depleted zone is conducted, the superincumbent horizon will be completed and produced. This procedure can be repeated until the entire reservoir is exploited. (Hossain and Al-Majed 2015) Figure 6 represents a cement plug abandonment of depleted reservoir horizons.

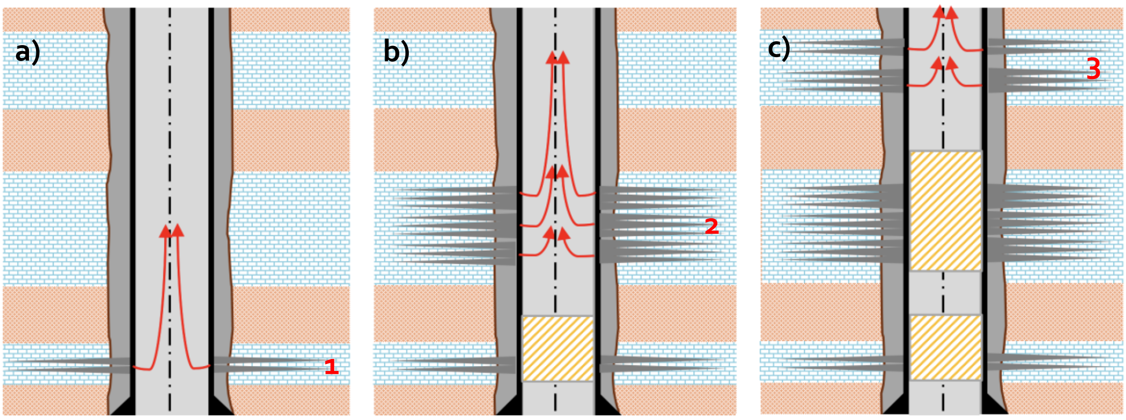


Figure 6: Abandonment of depleted reservoir zones with cement plugs

After exploitation of horizon 1 (6a) a cement plug (yellow) is set and the overlying formation 2 is perforated and produced (6b). In 6c, the last hydrocarbon bearing formation 3 of the reservoir is under production.

2.3.4 Isolation of a damaging fluids

Sometimes it is necessary to protect oil and gas producing horizons from damaging fluids such as water, other hydrocarbons or even cement slurries. In some cases, literature describes isolation of damaging fluids as the process described in 2.3.3, where cement plugs are set to abandon depleted zones and prevent unwanted water production from these horizons. However, Halliburton characterizes in one of their workbooks for cementing, isolation of damaging fluids as the process of protecting hydrocarbon formations during cement squeeze operations. Squeeze jobs, that are conducted above the pay zone may cause some cement slurry or other damaging fluids to enter the production horizon, leading to an unwanted damaging of the reservoir and shut down of the production. To prohibit such scenarios, cement plugs are set above the formation that has to be protected from the high-pressure squeeze operations. (Halliburton 2001)

2.3.5 Seal off Lost Circulation (LC) zones

Lost circulation or thief zones are formations that are highly permeable or naturally or artificially fractured. The latter, normally unwanted if excessive downhole pressure is applied that exceeds the fracture pressure of the formation. The mud flows uncontrolled into the zone and creates unstable wellbore conditions that may end up in well control issues. To identify if such a zone was penetrated and drilling fluid is lost, either the mud volumes pumped in- and out of the wellbore are compared (e.g. computer assisted, pump rate and flow paddle) or the mud level in the pit tanks are monitored. To stop the loss, lost circulation material (LCM) is added to the drilling fluid. If this first line of defence is not successful, cement plugs can be set across the thief zone. Nelson and Guillot (2006), describe the process as placing a plug above the LC horizon, that is slightly squeezed into the formation to ensure a good bondage between the cement and the formation of interest. In addition, LCM materials such as chemicals or fibres are added to the slurry to enhance the cement properties. Before the job starts the exact depth of the lost zone must be encountered (by comparing drilling reports with electrical image logs) and in addition the lithology of the section (e.g. gamma ray logs, cutting analysis) has to be evaluated. Depending on this information, the corresponding cement slurry can be mixed and pumped. (Nelson and Guillot 2006)

After the cement has set, the plug and consequently the formation can be drilled without losing fluids (Figure 7).

2.3.6 Provide a seat for directional drilling and side tracking

Different circumstances during drilling demand to plug back a part of the existing wellbore and initiate a sidetrack to reach the desired target. This can be either if a new horizon is explored using the directional drilling method, if wellbore conditions lead to a collapse of the borehole or if a fishing operation is uneconomic or unfeasible. The major problem when sidetracking a wellbore is to guide the bit into the correct direction or in case that fishing was not successful the issue that the fish blocks the drilling path. To bypass these problems a cement plug or so called whipstock plug can be set above the problematic area. The plug acts as a kick off point for the new hole and guides the bit into the correct direction (Figure 8). In order to perform a successful sidetracking job, the right composition of the whipstock slurry is important. According to Nelson and Guillot (2006) the compressive strength of the lithology that has to be drilled in the direction of the planned sidetrack must be smaller than the strength of the set cement, otherwise the plug will be drilled and the operation has to be repeated. Typically, whipstock plugs should have a compressive strength between 5,000 to 7,000 psi (35 to 49 MPa). In some cases, it is not possible to achieve a cement strength that is higher than that of the formation that has to be drilled. If this is the case, the cement must be reinforced to increase the toughness of the plug compared to that of the rock. (Nelson and Guillot 2006)

Loveland and Bond (1996) suggested to reinforce with polymer fibres to increase the impact resistance of the cement. Al-Suwaidi et al. (2001) recommend using ultra-lightweight cement blends that contain low-density particles with an optimal particle size distribution for achieving the right toughness.

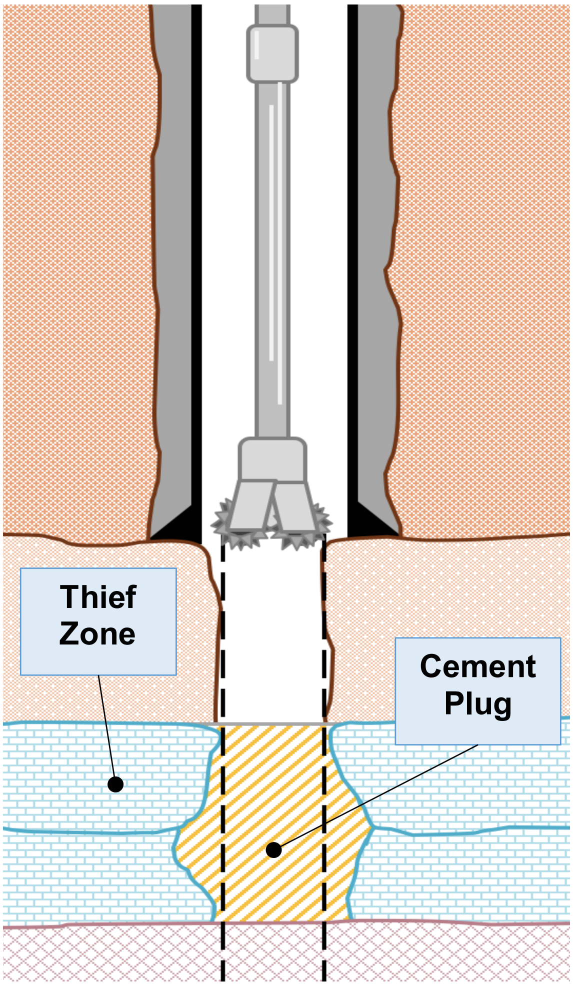


Figure 7: Cement plug seals off a LC zone
cf. Nelson and Guillot (2006)

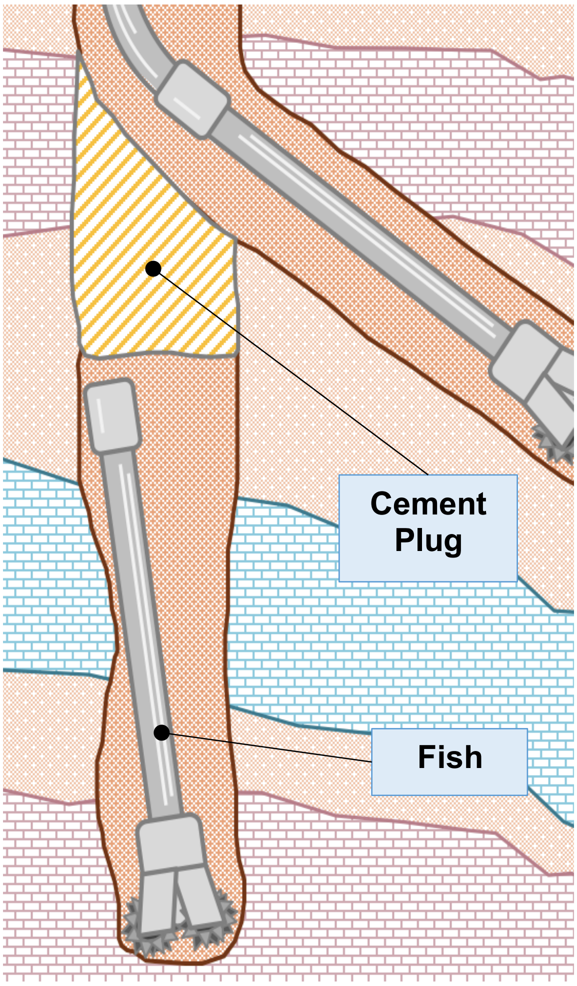


Figure 8: Cement plug used to sidetrack a fish
cf. Nelson and Guillot (2006)

2.3.7 Isolate a zone for formation testing

In some cases (e.g. during formation pressure testing), it is necessary to set cement plugs between formations with different rock specifics. If information from a zone is planned to be assessed via pressure tests but a different formation below suffers from a weak structure, cement plugs can be set between them to protect the weak horizon (Figure 9). Nelson and Guillot (2006) denote such installations as protective plugs or test anchor but state at the same time that it is only recommended to establish such cement protection plugs in an uncased OH section, alternatively bridge plugs are a better solution.

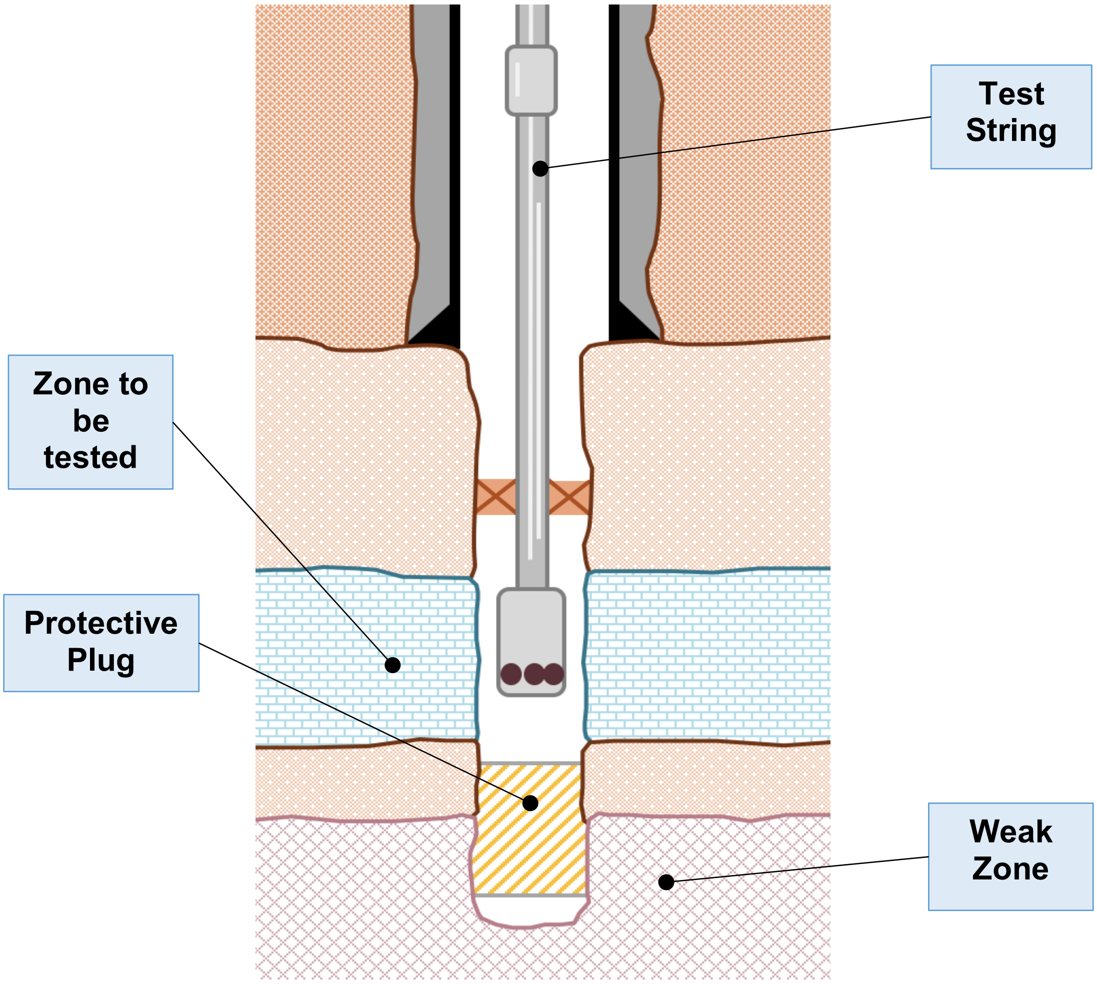


Figure 9: Cement plug set as a test anchor
cf. Nelson and Guillot (2006)

2.3.8 Fixing of casing or tubing leaks

The last field of application that is discussed in this thesis are cement plugs that are used to fix casing or tubing leaks. During production phase, casings or tubings may be corroded because of the appearance of acid gases or aggressive and corrosive fluids (Figure 10). A common technology to fix such corroded spots are cement squeeze operations where high pressure is used to squeeze the slurry into the damaged location. The problem arising with this technique is, that old casings or tubings may fail under the high pressures exerted during the execution. Hence further damage occurs and the squeeze job has to be rerun. Loveland and Bond (1996) evaluated that it is more protective to set cement plugs via coiled tubing (CT) technology across the damaged zone. Lower treatment pressures and less packer generated stresses (Nelson and Guillot 2006) promote a successful leakage repair.

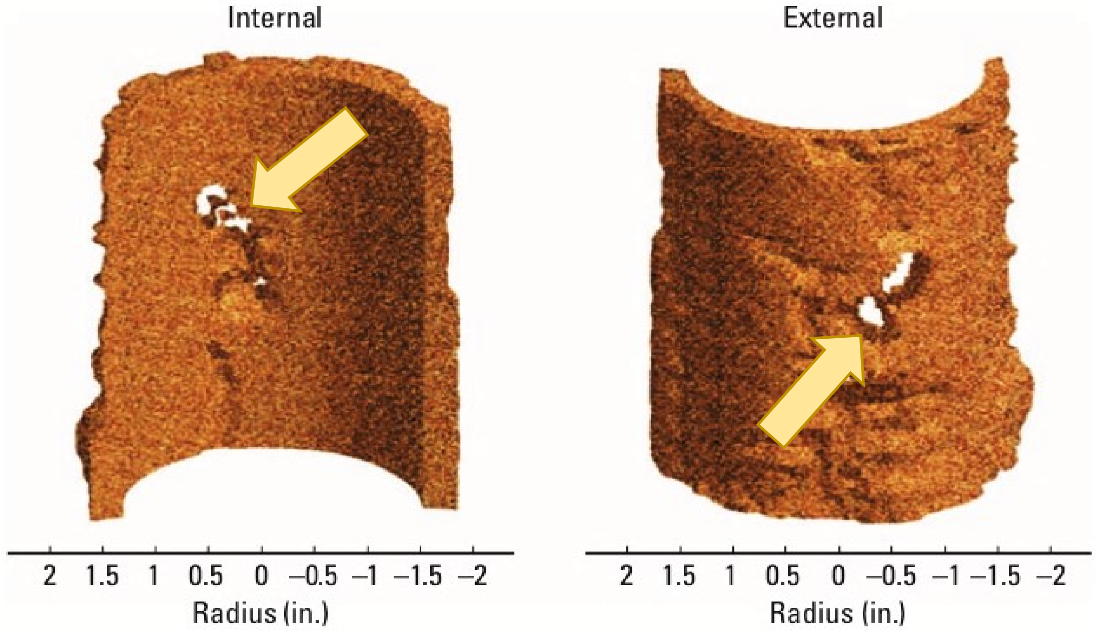


Figure 10: Three-dimensional casing leakage image

For worn and old corroded casings or tubings it is preferred to fix the leakage with a cement plug that is drilled after hardening process rather than using the high-pressure squeeze technology that can harm the integrity of the steel tubulars; (Nelson and Guillot 2006)

2.4 Cement Plug Setting Techniques

Plug Cementing is part of the remedial cementing technology and used for various reasons such as P&A, sealing off LC zones, as a test anchor for formation pressure tests or as kick off points for sidetrack drilling. Many countries have set up guidelines that must be followed by the oil and gas companies when setting a cement plug, especially when plugging a well permanently to guarantee full integrity and provide a seal against unwanted fluid flow. To do so, various plug setting techniques were invented by the engineers to place a cement plug across the area of interest. The following chapter describes the different technologies in more detail.

2.4.1 Balanced Plug Method

According to Roye and Pickett (2014), the Balanced Plug Method (BPM) is the most used conventional cement plug setting technique in the oil and gas industry. For setting the cement in place, a drillpipe, a tubing (e.g. coiled tubing) or a combination out of both tubulars (problems arising with the combination method will be discussed in Chapter 4.1.1.2) are run into the wellbore to the desired depth. The cement is mixed on surface and pumped through the pipes downhole. The key issue, why some cement plugs fail if they are set via BPM is the fact that the cement is contaminated with mud and other fluids during setting process. To keep the contamination on a low level, a pre-defined volume of spacer has to be pumped before and behind the cement slurry batch. The volume of the pre-cement spacer and post-cement spacer must be calculated in a way that their heights correspond to the same level in the annulus and in the drillpipe after setting the plug in place (Nelson and Guillot 2006). Heathman et al. (1994) invented a method that induces linear high velocity streams of drilling mud at the desired zone of interest. The injected drilling mud should remove gelled drilling fluid and mud cake from previous drilling events to provide a clean and uncontaminated contact area between the plug and the borehole wall. The linear flow behaviour of the injected fluid must be sufficient enough to transport the gelled mud and cuttings to the surface.

The BPM obtained its name from the fact, that after setting the cement slurry in place, the different fluid columns (cement, spacer) have the same height inside the pipe and outside in the annulus- therefore the name *balanced* (Figure 11a). According to Nelson and Guillot (2006), it is a common practice to under-displace the plug, meaning that the level in the pipe is slightly higher than that in the annulus (Figure 11b). This has the advantage that the pipe can be pulled dry (no flow back of drilling mud on the rig floor) and the chance of cement contamination during pulling of the drillpipe will be minimized. After the job is finished, the pipes are pulled out of the slurry carefully and the plug is balanced (Figure 11c).

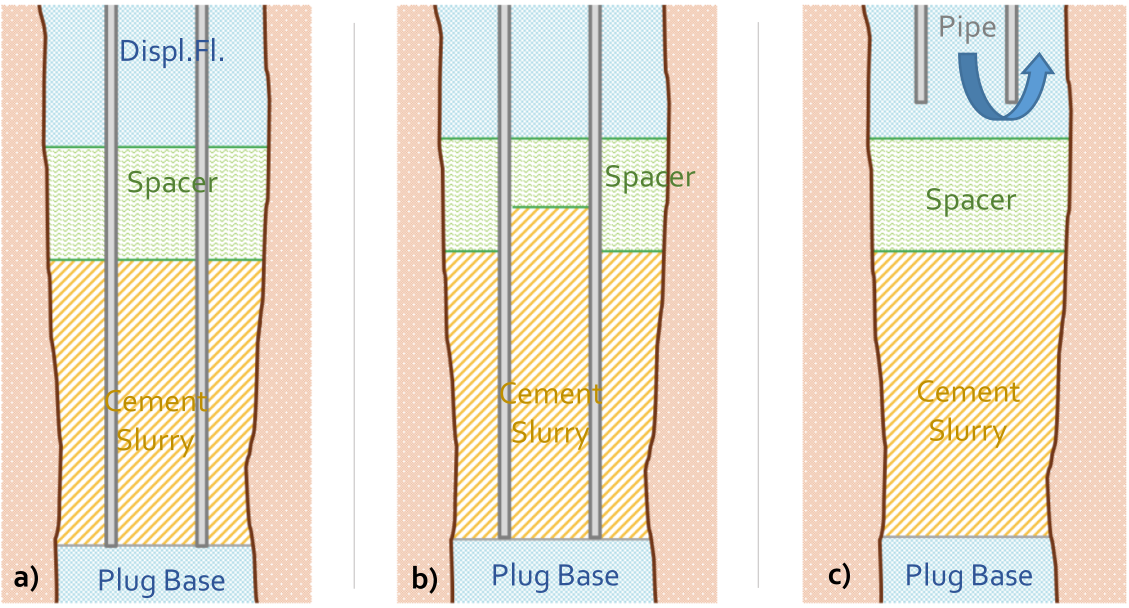


Figure 11: Scheme of the Balanced Plug Method

In Figure 11a all the fluids, used to set the cement plug have the same column height, therefore the name "balanced". The plug base is a viscous fluid with a high gel strength, hindering the cement to fall through, followed by the cement slurry, the spacer and the displaced fluid (bottom up). Figure 11b shows an under-displacement of the plug to avoid contamination of the cement when POOH and the ability to pull the pipe dry. Figure 11c shows the balanced plug in ideal case after pulling the pipe slowly out of the slurry. Ideally, no contamination of the cement has happened during POOH.

A good indication if the pumped fluids are balanced (as described in Figure 11a or 11b), can be obtained from the displacement pump pressure observed during the cementing job (Bourgoyne et al. 1991). Figure 12 represents an idealized displacement pressure profile, where the plug seems to be balanced if the pressure, recorded at the end of the job, equalizes the obtained pressure at the beginning.

Figure 12: Idealized pressure vs. time profile for a balanced plug job

(Bourgoyne et al. 1991) adapted from Mitchell et al. (2011)

The BPM can be used to set cement plugs in OH as well as in CH sections. To conduct the job successfully and to obtain balanced properties, the exact volumes of spacer and cement must be calculated. In case of an OH plug, a calliper log has to be run in the forefront to guess the average borehole diameter for precise calculation. As already stated in Figure 11, the plug needs a base where it can be set onto. This plug base can be either a mechanical bridge plug (in CH sections) or thixotropic bentonite suspensions or crosslinked polymer pills (Nelson and Guillot 2006).

The major failure mechanism for cement plugs that have been set with the BPM are contaminations with mud and other wellbore fluids during placement process and POOH. A sophisticated design of the plug base and accurate borehole conditioning may reduce the contamination. Nevertheless, plug cement contamination is a commonly known issue that will be discussed in more detail in Chapter 4.1.1.2.

2.4.2 Dump Bailer Method

The dump bailer consists of a barrel that is linked to a wireline cable. The barrel itself holds a pre-defined volume of cement that is mixed at surface, filled in the vessel and finally lowered to the desired point of interest. In contrast to the BPM, where the cement is placed either on a mechanical device or high viscous pills, dump bailer cement is placed across a pre-installed bride plug or cement platform. The bailer can be opened mechanically by touching the mechanical plug or electrically where e.g. an actuator is activated after a default time delay, which allows then the hydrostatic wellbore pressure to enter a piston chamber that opens the cement ports. The dump bailer can only hold small volumes of cement and was initially invented to set plugs in surface regions. Nowadays, wireline cables are very strong and durable and therefore dump bailer cementing is also performed in deeper well regions. Nelson and Guillot (2006) describe the problem of slurry design during wireline running. Because of the fact, that the cement is stationary in the barrel during the run, the design must be chosen in a way that the slurry provides sufficient flow properties when the bailer has landed. In other words, the cement must be retarded to avoid previous gelation in the barrel, especially in high temperature wells. Dump bailer runs are relatively inexpensive but consume time since only small volumes can be set. The runs can be repeated until the desired cement column is reached.

2.4.3 Two-Plug Method

The plug method is a derivative form of the BPM, allowing a more precise setting of the plug with only little contamination. The noun "two-plug" refers to the fact, that two wiper plugs (either rubber plugs or foam balls that wipe the inner surface of the pipe clean) are pumped between the actual cement slurry. After the initial spacer was pumped, the first plug or bottom plug is released into the string, with the intention to clean the workstring from drilling- and other contaminating fluids. During that stage, the cement slurry is mixed and also pumped down the wellbore, followed by the second plug or top plug, spacer and finally drilling mud. The top plug separates the cement from the contaminating drilling fluid ahead. A sub connects the end of the drillstring with an aluminium tailpipe (Nelson and Guillot 2006), that can be sheared off and drilled trough in case that the string is not pulled in time and gets stuck in the cement during operation.

When the bottom plug has landed in the designated tailpipe widget, surface pressure is increased to rupture the diaphragm of the plug. As a result, cement slurry can pass through the bottom plug and placed at the selected depth. Subsequently, a pressure spike at the surface indicates that the top plug has landed on the bottom one and the cement is set in place. To restore pipe circulation conditions, the top plug is sheared by applying surface pressure leading spacer and mud to pass both plugs. Finally, the workstring has to be pulled carefully but quickly out of the cement column, to prevent early cement setting and a stuck string. If the string is stuck, the tailpipe can be sheared off as explained above.

The two-plug method is a sophisticated and well-tried cement setting method, but in comparison to the noticeably simpler BPM requires more resources, more lead time, careful job planning and a well experienced cementing crew.

2.4.4 Umbrella Shaped Membranes

By far the most applied cement plug setting technique is the BPM (Roye and Pickett 2014), because it can be deployed straightforward without much lead time or extra resources, but often struggle from slurry contamination during placement. Harestad et al. (1996) invented as a consequence a new tool that assists the setting procedure when the BPM is applied. The umbrella shaped tool consists out of fiber glass rods with canvas in between them and helps to separate the cement slurry from the contaminating drilling mud. The tool can be used from 6 in. to 23 in. borehole diameter and has to be set before the cement job is conducted. It was specially designed for the application in OH sections, because of its flexibility and adaptability. Harestad et al. (1996) also states, that the tool is not a hydraulic barrier that controls losses further down in the well. Other separation tools with the same or similar functionality are also available.

2.4.5 Drillable Aluminium Pipes and Inflatable Packers

Nelson and Guillot (2006) describe the deployment of inflatable packers in combination with drillable aluminium pipes. The packer- pipe combination is run into the borehole to the desired depth where the plug has to be set. The packers are set by pumping cement slurry downhole, resulting in an expansion of the elastomers. After opening the ports of the aluminium pipe, the plug is set with the balanced plug method (see 2.4.1). When the job is executed, the drillable pipe is left in place and disconnected from the DP. If the packers are set correctly, they provide a good mechanical cement plug base, that prohibit cement slurry from falling down the wellbore due to gravity. The disadvantage is, that packer elastomers are sensitive against sour and corrosive environments where they tend to degrade and finally fail. This problem is more related to the production phase, since the exposure time of packer elastomers in such sour environments are much higher, compared to the time during drilling phase. Lam et al. (2001) developed as a consequence, a packer type that consists out of an aluminium basket, containing no elastomers at all. The basket is expandable and can be run through tubings and set in a large range of borehole diameters, in OH and in CH sections. The basket forms a mechanical platform for the cement plug similar to that of a conventional packer. It is applicable in H_2S, CO_2 and sulphuric environments, but would be degraded in a chloride or very low pH ambiance, since aluminium is sensitive against it. Lam et al. (2001) describes the aluminium cement packer as a cheaper solution compared to normal bridge plugs which can be used during workover jobs for preventing debris and other material to fall down the borehole or as a plug base for abandonment or zonal isolation plugs (see 2.3.1 to 2.3.4).

2.4.6 Cement Retainer Method

The cement retainer method is mentioned as an alternative way of getting cement slurry under high pressure in a borehole, using tools with inflatable packers. The method is part of the remedial cement squeeze technology (see Figure 2) and not covered in more detail in this thesis.

2.5 Cement Plug Verification and Evaluation

After cement plugs have been set, they must be verified according to their functionality, integrity and length (TOC level). Before verification can start, it is of importance to keep the designated WOC time in mind, otherwise cement quality might not be sufficient enough to withstand the test procedures.

2.5.1 TOC Evaluation

The TOC of a plug is normally evaluated and controlled by tagging. Tagging means that a DS with a BHA is assembled RIH and the top of the plug is tagged to verify its actual depth. To do so, the calculated TOC of the plug has to be evaluated- this will guide the amount of DP the driller needs to trip in order to land above the plug. If the DP is landed some stands above the calculated depth, pumps have to be switched on to ensure a circulating system. Afterwards, the DS is lowered until the top of the plug is tagged. Based on the BHA length and the number of DP that were tripped in, the real TOC can be evaluated and compared with the calculated one.

2.5.2 Plug Evaluation

Most of the discussed plugs can be evaluated, simply by executing the next planned step of the well construction operation and evaluate if the plug holds and fulfils its demands. If the plug fail, the job has to be repeated. Intensive planning, simulating and proper designing of the plug job can minimize the error rate. Nevertheless, plugs have to be evaluated, where special attention has to be paid on abandonment plugs, since governmental regulations require special verification parameters to ensure an eternal integrity.

2.5.2.1 Abandonment Plug Evaluation

Abandonment plugs require a special verification process since the plugs have to withstand pressures and hydrocarbon migration eternally. According to Haidher (2008), the quality and integrity of an abandonment plug is tested by charging weight on the plug, drill through it and finally apply pressure against the cement. If the assessed ROP, when drilling the cement top, is less than 5 feet/hr a good quality plug was performed. If the ROP is between 5-10 ft/hr, the quality is acceptable and agreed by most of the authorities.

2.5.2.2 Kick-off Plug Evaluation

The quality of a kick-off plug is normally simply evaluated by kicking off the borehole. If the requirements (strength, time for WOC, bonding...) were met, the plug is of good quality and will guide the bit in the designated direction.

2.5.2.3 LC Plug Evaluation

According to Nelson and Guillot (2006), LC plugs are evaluated by comparing the fluid loss rates before and after the treatment. If the losses after the treatment are minimized or vanished, the plug exhibits a good quality.

Chapter 3 Cement Composition and Characterization

Cementing operations are an essential and important component during well construction, well intervention and wellbore abandonment. The requirements on the cement and his characteristics are high, not least because functionality, safety and well integrity should be assured eternally. The most popular and widely-used cement type in the oil and gas industry is the so-called Portland Cement. The following chapter discusses the manufacturing, chemical characteristics and composition of the Portland Cement as well as it's use and API classification in the oil and gas industry.

3.1 Portland Cement- Manufacturing and Chemical Characteristics

"Opus caementitium" was the name for the ancient cement that was used by the romans to build their empire. This type of cement has only little similarities to our todays used Portland type, but the romans have found a construction material that had ideal features in terms of pressure resistance and water insolubility- characteristics that are also important in the oil and gas cementing business today. By the invention of a predecessor of the Portland Cement during the middle of the 19th century and by a redevelopment at the beginning of the 20th century, engineers evolved that, what is today known as the Portland Cement. The Portland type is a hydraulic cement that can harden not only under surface conditions but also under water and applies his compressive properties due to hydration processes.

Portland Cement consists of different percentages of pulverized clinker and a small percentage of gypsum (Figure 13). Clinker is burnt raw material that is processed in a rotary kiln at 1450°C temperature, followed by a sophisticated cooling process and grinding procedure (Piklowska 2017). After an aging process, gypsum (1-3 w%) is added to control the strength and setting time of the product (Mitchell et al. 2011). Lerch (1946), investigated the influence of gypsum content on the hydration process of different Portland Cement pastes and found out, that there is an optimum sulfate content that positively influences the strength of the cement. Beyond that particular threshold, compressive strength properties will decrease.

According to Nelson and Guillot (2006), *calcareous material* (raw material type 1) and *argillaceous material* (raw material type 2) are needed to manufacture Portland clinker. Both raw materials can be either naturally occurring ones or artificial industry products. Natural sedimentary *calcareous material* are limestone, shells and corals whereas artificial ones are precipitated calcium carbonate and other different industry waste materials. Natural *argillaceous materials* are typically shale, clay, marl, mudstone, volcanic ashes and alluvial silts (depending on the natural occurrence not all Portland types are available in all countries of the world), whereas artificial ones are blast-furnace slag and fly ash from steel mills and coal operated power plants. (Nelson and Guillot 2006)

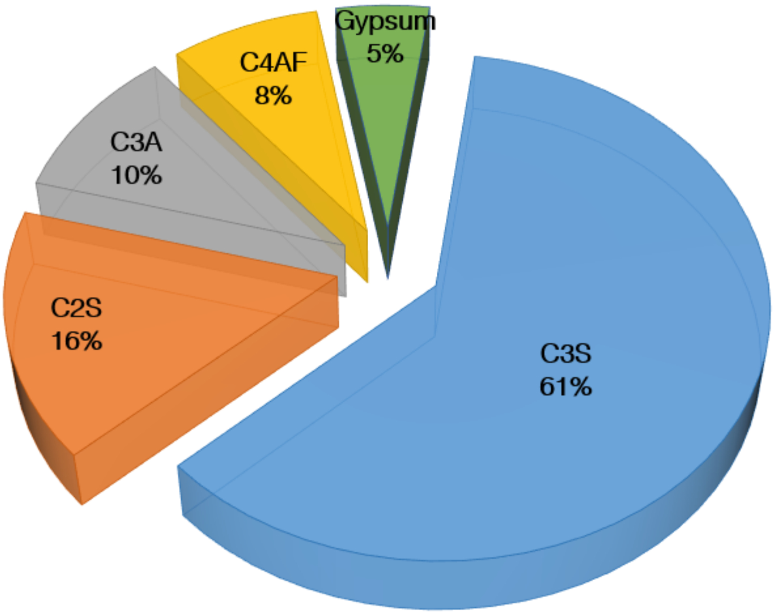


Figure 13: Typical Portland Cement composition
cf. MIT Concrete Sustainability Hub (2013)

The raw material type 1 provide the calcium oxide, whereas the raw material type 2 introduce the oxides of aluminium and silica components to the Portland cement (Piklowska 2017). The relationship is displayed in Figure 14. Depending on the percentage and mineralogical characteristics of the clinker, different Portland cement types and properties can be achieved. The oxides take up more than 95% of the overall composition of a typical Portland Cement (Nelson and Guillot 2006). Depending on the raw material and the processing, the percentage of different oxides can fluctuate but are normally in a typical range that is displayed in Table 2.

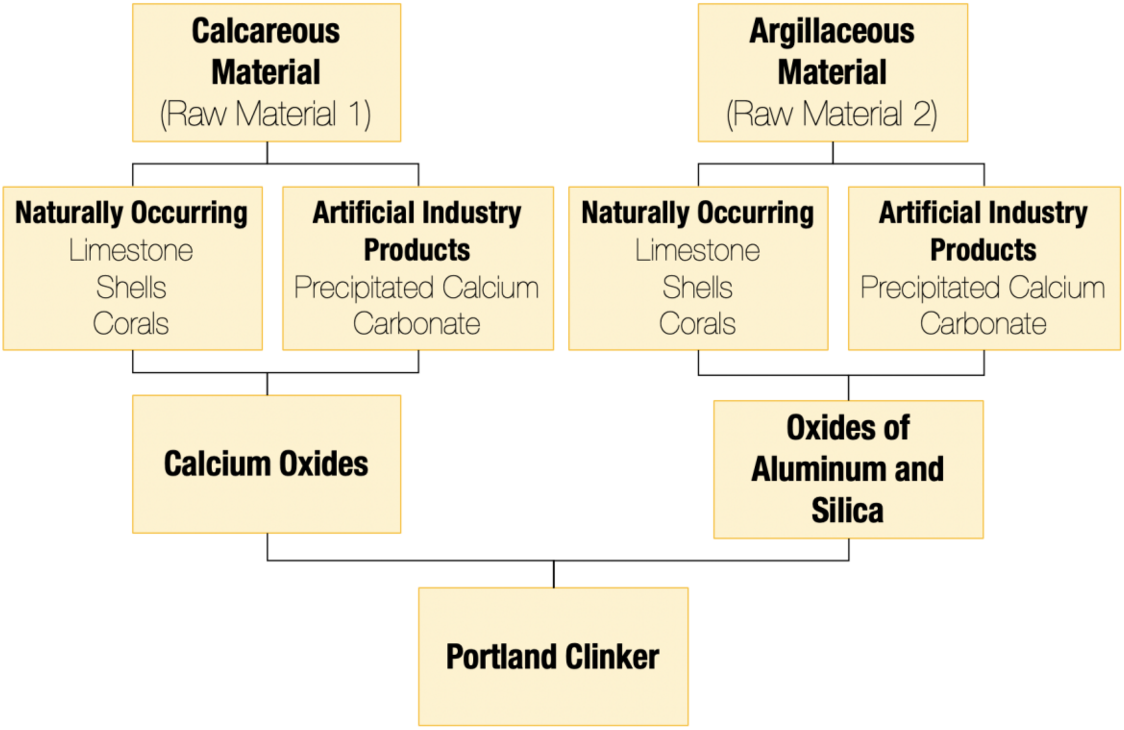


Figure 14: Relationship between raw material and Portland Clinker

Oxide Name	Formula	Percentage
Calcium Oxide	CaO	60-70%
Silica Oxide	SiO_2	18-22%
Aluminium Oxide	Al_2O_3	4-6%
Iron Oxide	Fe_2O_3	2-4%

Table 2: Typical oxide distribution of a Portland Cement
cf. Nelson and Guillot (2006)

One important parameter that should be mentioned in this chapter is the special chemical notation that was introduced by chemists to make the reading and writing of the chemical compositions of the cement easier and shorter. The notation uses abbreviations for given oxides to simplify the reading. The abbreviations can be seen in Table 3. Tricalcium silicate (an oxide that is responsible for the setting and development of the early strength of the cement) for example, can be written as $Ca_3S_iO_5$ or $3CaO \bullet SiO_2$. Using the abbreviations, we can simplify the Tricalcium silicate notation from $Ca_3S_iO_5$ to C_3S, indicating that we use 3 parts of calcium oxide (CaO) and one part of silica oxide (SiO_2).

$C = CaO$	$F = Fe_2O_3$	$N = Na_2O$	$P = P_2O_5$
$S = SiO_2$	$M = MgO$	$K = K_2O$	$f = FeO$
$A = Al_2O_3$	$H = H_2O$	$L = Li_2O$	$T = TiO_2$

Table 3: List of abbreviations used for the chemical notation of cement compositions
cf. Nelson and Guillot (2006)

The characteristics of the Portland Cement is mainly influenced by the distribution of the different clinker components. According to Piklowska (2017), the mineralogical composition is influenced by four basic clinker compounds:

- $3CaO \bullet SiO_2$ (C_3S), also known as *alite*- C_3S is the most distributed component of the Portland Cement blend. Alite reacts relatively fast with the water phase and is responsible for the slurry setting as well as the formation of early strength properties of the cement. Cements containing a higher number of C_3S are characterized by a fast build- up of strength and high level of endurance but suffer from high shrinkage and increased hydration heat.
- $2CaO \bullet SiO_2$ (C_2S), also known as *belite*- C_2S is less reactive during early aging phase but influences the final strength of the cement slurry. Belite has a lower hydration rate compared to alite and therefore only influences the late time period of the cement slurry.
- $3CaO \bullet Al_2O_3$ (C_3A), also known as *celite*- C_3A affects the bonding speed of the slurry and accelerates the bonding characteristics, by providing a large quantity of heat. High sulphate resistant cements will be affected only little by the celite properties.

- $4CaO \bullet Al_2O_3 \bullet Fe_2O_3$ (C_4AF), also known as *brownmillerite*- C_4AF affects the strength properties over time of the cement slurry. The brownmillerite component is the smallest fraction in a typical Portland Cement blend.

Table 4 shows the typical mineralogical composition of oilfield Portland Cement clinker, where each phase influences the properties of the cement slurry as described above.

Oxide Composition	**Notation**	**Name**	**Percentage**
$3CaO \bullet SiO_2$	C_3S	Alite	55-65%
$2CaO \bullet SiO_2$	C_2S	Belite	15-25%
$3CaO \bullet Al_2O_3$	C_3A	Celite or Aluminate	8-14%
$4CaO \bullet Al_2O_3 \bullet Fe_2O_3$	C_4AF	Brownmillerite of Ferrite Phase	8-12%

Table 4: Typical mineralogical composition of Portland Cement clinker used in the oil & gas industry
cf. Nelson and Guillot (2006)

3.2 Hydration Process

As already stated and also displayed in Table 4, typical Portland Cement consists among gypsum also out of *silicate phases* (C_3S and C_2S) and *aluminate phases* (C_3A, C_4AF), where the silicate phases take up the highest proportion (up to 80%). Both, the silicate and the aluminate hydration influence the character of the Portland Cement and will now be discussed in more detail.

3.2.1 Hydration of silicate phases

Alite and belite are the silicate phases in the Portland clinker blend. Although both are silicates, alite and belite react completely different from each other and influence the cement properties in various ways. When mixed with water, a reaction will take place that form *calcium silicate hydrate* (C-S-H) and calcium hydroxide (CH). According to the MIT Concrete Sustainability Hub (2013) the principal chemical reactions look as followed:

$$Alite\ Reaction: C_3S + 5.3H \rightarrow\ C_{1.7} - S - H_4 + 1.3CH$$

$$Belite\ Reaction: C_2S + 4.3H \rightarrow\ C_{1.7} - S - H_4 + 0.3CH$$

Where C-S-H is the main binding and hardening unit and responsible for the development of the cement strength and durability. The calcium hydroxide (CH) fraction is a byproduct of the reaction. MIT Concrete Sustainability Hub (2013) mentions, that the calcium hydroxide does not influence the strength of the concrete directly but keeps the pH in a state, that reinforced steel will be kept in a passivated level and therefore becomes resistant against corrosion. The equations also show, that C_3S produces approx. four times as much calcium hydroxide as C_2S does. Calcium hydroxide does not contribute to the cement strength, and therefore the belite reaction should be preferred. A reduction in CH will result in an increase of strength, but because of the fact that C_3S reacts much faster compared to C_2S when added to water, and also because C_3S is responsible for the early setting and strength development of the cement, C_3S reaction is preferred. An answer why alite reacts faster than belite, is addressed by the MIT Concrete Sustainability Hub (2013), where experiments and research on atomic scale models have shown that C_3S has a more "defective" crystal structure, compared to the more "perfect" structure of C_2S. The defective C_3S structure suffers from the fact that not all appropriate sites of the alite crystal is filled with oxygen. This allows the water to enter the "defective" C_3S structure easier, resulting in an accelerated hydration process. However, the more "perfect" structure of C_2S crystals retard the hydration process.

Calorimetry curves can be used to state the exothermal reaction phases that take place during setting of the cement slurry. Figure 15 shows such a calorimetry curve for alite (C_3S) hydration. The curve is split into five different hydration phases (MIT Concrete Sustainability Hub, 2013):

- **Preinduction Period (I)** → initial reaction period where approx. 1- 2% of the alite reacts.
- **Induction Period (II)** → time period that occurs shortly after mixing process. Here, only very low reactivity happens. That period is of importance, because it purports the mixing, pumping and placing time of the cement. For C_3S the induction period is smaller than for the C_2S.
- **Acceleration Period (III)** → at this time period, the setting and strength development of the slurry begins, highest hydration rates achieved here.
- **Deceleration Period (IV)** → further setting at decreased hydration rates compared to Period III, cement strength continues to develop.
- **Diffusion Period (V)** → hydration continues at decreasing rate; cement strength develops and no major structural changes at this phase. According to Nelson and Guillot (2006), diffusion period duration is infinite at ambient conditions and total hydration will never be reached, because precipitated Protlandite crystals (calcium hydroxide) cover and wrap hydrating C_3S particles.

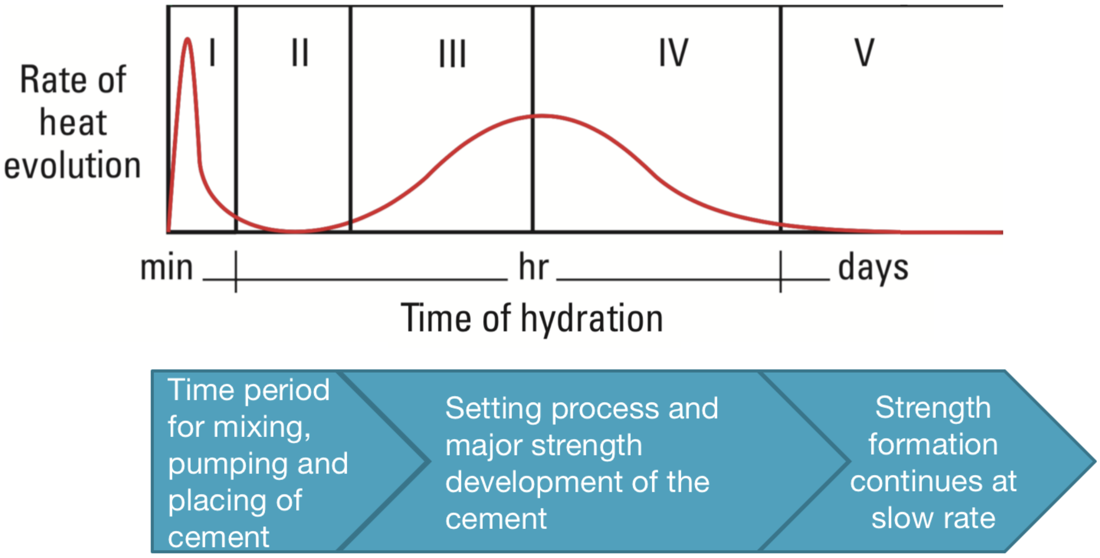


Figure 15: Calorimetry curve for C_3S hydration
Adapted from Nelson and Guillot (2006)

3.2.2 Hydration of the aluminate phases

The aluminate phases celite (C_3A) and brownmillerite (C_4AF) are the smaller fraction of the Portland cement clinker blend but also contribute their features to the performance of the slurry. During the hydration process, the aluminate phases undergo a reaction with the calcium sulfate from the added gypsum fraction. According to Nelson and Guillot (2006), C_3A and C_4AF are most reactive during early hydration phase and provide an important influence on the rheological properties of the slurry. Furthermore, aluminates contribute to the strength development at short aging time.

3.3 API Cement Classification

According to the American Petroleum Institute (2005), oil well cements are subdivided into 8 classes (A-H), where the arrangement was made according to their depth of application, temperatures and pressures as well as three different grades (O= ordinary, MSR= moderate sulfate resistance and HSR= high sulfate resistance). The requirements for oil and gas well cements differ from classic construction works cements. Especially physical properties such as viscosity, thickening time and strength are important factors that have to be considered. The viscosity and thickening time guide the possibility for pumping and placing of the slurry and strength properties influence setting time and cement quality (Morgan 1958). As a result, the American Petroleum Institute (2005) came up with the classification of the oil well cements as followed:

- **Class A:** Grinded Portland Clinker that consists out of hydraulic calcium silicates (major constituent) and calcium sulfate as an inter-ground additive. Processing additives (additives that do not influence the oil well cement performance) may be used during manufacturing period of Class A cement but are an option of the manufacturer. *Class A cement is only available in grade O.*

- **Class B:** Grinded Portland Clinker that consists out of hydraulic calcium silicates (major constituent) and calcium sulfate as an inter-ground additive. Processing additives (additives that do not influence the oil well cement performance) may be used during manufacturing period of Class B cement but are an option of the manufacturer. *Class B cement is intended for use when moderate to high sulfate resistance is needed and is available in MSR and HSR grade.*
- **Class C:** Grinded Portland Clinker that consists out of hydraulic calcium silicates (major constituent) and calcium sulfate as an inter-ground additive. Processing additives (additives that do not influence the oil well cement performance) may be used during manufacturing period of Class C cement but are an option of the manufacturer. *Class C cement is intended for use when high early strength is required and is available in O, MSR and HSR grade.*
- **Class D, E and F:** Grinded Portland Clinker that consists out of hydraulic calcium silicates (major constituent) and calcium sulfate as an inter-ground additive. Processing additives (additives that do not influence the oil well cement performance) may be used during manufacturing period of Class D, E and F cement but are an option of the manufacturer. Furthermore, so called "suitable set-modifying agents" can be added by the manufacturers option. *Class D, E and F cement is intended for use under moderately high temperatures and pressures and are available in MSR and HSR grade.*

  Class D, E and F are also called "retarded cements" where the retardation is achieved by increasing the particle size and reducing the C_3S and C_3A fraction, since they contribute to early setting of the cement. Because of the invention of chemical retarders that can be easily added to Class G and H cements, Class D, E and F are seldom used in the oil and gas business today. (Nelson and Guillot 2006)
- **Class G and H:** Grinded Portland Clinker that consists out of hydraulic calcium silicates (major constituent) and calcium sulfate as an inter-ground additive. No other additives than calcium sulfate or water are allowed (no processing additives are allowed!) to be blended with the class G or H clinker. *Class G and H cement is intended for the use as a basic oil and gas well cement and is available in MSR and HSR grade.*

  Class G and H have in principle the same composition but differ in the grain sizes of the clinker material. Class H cements have a coarser structure compared to class G cements.

Mitchell et al. (2011) also describes the importance of the "normal" or "API water" content of the different cement types in order to provide uniformity during testing. The API water content is the % of water, per weight of cement to be added to the API cement type respectively. A table with the typical calcium silicate composition, as well as different physical and chemical requirements can be found in the Appendix (Figure 83). Furthermore, the water ratios for the cement are also provided in the Appendix (Figure 84).

3.4 Cement Plugs- Cement Design

In the last decades, not much attention was paid on cement plug slurries. Instead all effort was pushed into optimizing casing and liner cementing, in order to reduce NPT and LT issues addressed to this well construction part. However, plugs that are set ineffectively consume unnecessary rig time too. According to Diaz et al. (2009), deep Southern Mexico exploration wells consume an average of 8 to 10 rig days until a usable kick-off plug is set successfully. This implements the fact, that also cement plug slurries must be designed in a proper way to fulfil the operational requirements in order to reduce unnecessary rig time. Some important guidelines for the slurry design will be discussed on the following page.

The most common oilfield cement type is the API Class G and H cement. This cement classes are well proven, tested and applied slurries that are relatively easy to handle and available nearly on all drilling places of the world. Therefore, also cement plugs are composed out of the standard API Class G/H cement, where the application of modified class H cements became extremely popular in the last few years (Mitchell et al. 2011). According to the API standard, no other additives than calcium sulfate and water are allowed to add during production process. This make the cements perfect for oilfield applications, since individual and field specified additives can be easily subjoined to the slurry without gaining the risk of interacting with the manufacturer additives, as it might be the case with the other API cement classes (A-F). Each plug type is designed and set to fulfil different tasks. The most important parameters that should be considered for plug slurry design are:

- Adequate thickening time → enable an exact and successful placement of the plug
- Fast development of strength → especially important for kick-off plugs, since many plug operations fail because the time required for WOC is often not maintained
- Good bonding between casing/rock and the cement plug → fundamental parameter for abandonment plugs to prevent fluids from migration, but also important for kick-off plug systems where a bad bonding might lead to a failure to the drill bit to change direction or rotation of the plug when drilling forces are introduced (James F. Heathman et al. 1994)
- Compatibility with treatment fluids → cement plugs must withstand acids like HCl and HF
- General chemical resistance → resistance to oil and gas fluids as well as brines and corrosive media
- No shrinkage of set cement → important for abandonment plugs, where shrinkage might influence the integrity of the system and lead to gas or hydrocarbon migration
- Strength and toughness of cement → important for kick-off plugs, where the strength of the plug must be higher than the strength of the drilled rock in order to prevent a breakdown of the sidetrack operation. To improve the strength and toughness of the cement plug, several additives are available. Baret, Leroy-Delange, and Dargaud (1999) invented the application of amorphous cast metal fibers that, if added at 3% to 15% by weight and at lengths between 5-

10mm, significantly increase the strength and toughness of the cement system. Silica flour will increase the compressive strength under high temperatures and the addition of particulated rubber (Nelson and Guillot 2006) improves the impact resistance and flexural strength of the cements.

- Lost circulation prevention → according to Nelson and Guillot (2006) LC plug slurries should have a thixotropic or low density property. However, Putra et al. (2016) stated that low density slurries might collapse if applied in deep wells because of the crushing of the cenospheres in the slurry. They invented a soda-lime borosilicate glass system with a specific gravity of 0,39 to 0,45 SG and a particle size of approx. 50 microns resisting a crush strength of 8000 psi. Additionally, silica-based fibers were added which act as a LCM.

3.4.1 Additives

Additives enhance the possibility of applying oil and gas well cements successfully in different environments. High temperatures, corrosive media, high pressures, weak formation structures or high strength and toughness characteristics are some of the features that can be controlled and modified by additives. These auxiliary means are fine powders that are either dry blended to the cement material before transportation to the rig site or dispersed in the water during mixing process directly at the drilling location (Mitchell et al. 2011). According to Nelson and Guillot (2006), more than 100 different well cement additives are available. The exact cement manipulation of additives as well as different additive types and their adaptability is well discussed in many papers and other thesis, therefore only the most important functional groups will be discussed below. Additives that may be used during laboratory experiments are described in the respective chapters.

Different functional groups:

- Accelerators → decrease the setting time e.g. Calcium Chloride ($CaCl_2$)
- Retarders → retard the setting time e.g. lignosulfonates
- Weighting Agents → increase cement slurry density- similar to drill fluid weighting agents e.g. barite ($BaSO_4$), hematite (Fe_2O_3)
- Extenders → decrease the cement slurry density e.g. clays, N_2
- Dispersants → decrease the viscosity of cement slurries- similar to drill fluid dispersants e.g. lignosulfonates and various polymers
- LC Additives → bridge the pores and fractures of the loss zone e.g. walnut shells, or as discussed above silica-based fibers
- Others → these include antifoam agents, anti-gas migration additives or strength enhancing agents e.g. amorphous cast metal fibers or silica flour

Chapter 4 Common Industry Related Cement Plug Challenges

So far, the author has given an overview about different cement plug types and regulations, various setting procedures and plug evaluation methods as well as most prevalent cement compositions and characteristics. The following chapter addresses most common cement plug issues that are experienced by the oil and gas industry with a focus on kick-off plug and LC plug issues. The chapter highlights the technical challenges that occur during cement plug job operations and their probable corresponding reasons as well as a root cause analysis and the economic impact of these issues.

Although cement plug job evaluation has become more popular since the last decades and best practice methods were implemented, still many of the plug operations fail or result in an ungratified performance for further planned drilling steps. Research has shown, that the industry still struggles with cement plug placement and plug specifics, resulting in massive increase of non-productive time (NPT) costs and additional hours spend in fixing problems. J. Heathman and Carpenter (1994) showed that the industry average is 2,4 attempts until a kick-off plug was marked as a success. Farahani, Brandl, and Durachman (2014) still mentioned, that the industry success for setting cement plugs is 2,4 attempts. One can see, that in 20 years of research, advancements and improvements problems still occur. In fact, the oil and gas wells drilled today, are sometimes more complex and challenging but nevertheless, the basic parameters did not change a lot.

To rate and evaluate the most common plug issues, a failure characterization is implemented. The characterization focusses on LC plugs but mainly on kick-off plugs because on the one hand kick-off plug operations are responsible for most of the NPT and LT issues (J. Heathman and Carpenter 1994) and on the other hand the two plug groups are normally used during conventional drilling operation or well intervention. Hudson, Sones, and Eulberg (2015) characterized plug failures into two different groups. Group one covers *plug cements that fail to achieve their desired specifics* and group two includes *failure of removing workstring from the cement plug*. The author of this thesis will add two additional groups to characterize the technical issues in more detail. Group three examines *cement plug base failures* and group four deals with *bonding failures between the cement plug and the system*. To summarize, following four main failure characterization groups are implemented:

- **Plug cements that fail to achieve their specifics** → include misinterpreted temperature influence, cement contamination, slurry induced losses, inefficient strength properties, early setting problems, inadequate cement volumes
- **Failure of removing workstring from the cement plug** → include swabbing effects when POOH, over displacement issues, differential sticking problems when fixing LC zones

- **Cement plug base failures** → include incompetent cement plug bases, boycott effect in deviated boreholes, insufficient density equilibrium between cement and plug base
- **Bonding failures between cement plug and system** → include insufficient annular velocity and erodibility, mud removal problems in ERW, rotation of plugs when drilled out, insufficient spacer design

Some issues may not only influence one of the groups but also have an impact on other parameters and group specifics which lead ultimately to the plug failure. The following pages will discuss the individual groups, their challenges and if available also some solutions in more detail:

4.1 Technical challenges

4.1.1 Plug cements that fail to achieve their specifics

This group type includes most of the cement plug issues and has a considerable impact why many of the plug jobs fail. If one designs a cement plug, these problems have to be respected and analysed in the forefront anyway to decrease the chance of a failed plug operation.

4.1.1.1 Temperature influence

The estimation of the correct bottomhole temperature or to be more accurate the plug location temperature, is one of the most important parameters for slurry design and paradoxically one of the most underrated drivers.

When talking about temperature influence, one has to categorize mainly three different downhole temperature types. Engineers distinguish between bottom hole static temperature (BHST), bottom hole circulating temperature (BHCT) and the temperature differential. The BHST is the temperature that can be measured if no fluids are circulating and no cooling effect is developed. The BHCT is the temperature that the slurry will see as it is placed in the wellbore where a cooling effects occurs due to the circulation of mud, spacer and cement. The BHCT influences the cement placement time and ultimately the addition of several additives such as retarders. The third type is the temperature differential that plays only an important role during primary cementing operations where long cement columns are set with large temperature differences between the top and bottom of the cement column. (Mitchell et al. 2011; Nelson and Guillot 2006)

J. Heathman and Carpenter (1994) have found out, that oil companies give only little priority to temperature estimation. In many cases operators only rely on available thermal gradient data, but temperature gradients within a specific area or within a wellbore can vary dramatically (Farahani, Brandl, and Durachman 2014). J. Heathman and Carpenter (1994) reported even from operators that added some "safety" to the approximated temperatures. As a consequence, cement slurries were often highly over-retarded which has a significant impact on WOC time and strength properties for kick-off plugs. Circumstances get even worse in HPHT wells where an accurate BHCT estimation with computer-based simulation is essential.

When setting e.g. kick-off plugs in deep offshore wells, further problems can occur. Ravi et al. (1999) describes the influence of low seawater temperatures on the slurry properties. When the slurry is pumped downwards, a cooling effect of the low temperatures take place. If this effect is not considered during design phase, wrong BHCT are assumed that lead to insufficient plug properties. If temperature decreases, slurry hydration rate also decreases, leading ultimately to a massive increase of WOC. If the setting time is misinterpreted, plug strength development is insufficient and the bit fails to kick-off from the desired location.

4.1.1.2 Cement Contamination

Plug cement contamination is one of the biggest man-made problems that lead to plug failures. This subchapter deals with contamination problems related to slurry movement in the workstring, where the intermixing of different fluids causes the cement to fail its specifics. Nevertheless, this part is strongly linked to subchapter 4.1.2.1 where contamination issues are discussed that are connected to failures in removing the workstring from the slurry.

A frequent problem which occurs especially in ERW and long horizontal well sections is discussed by Haidher (2008), where the normally relative small cement plug volume gets easily contaminated by the subsequent fluids because of the long travel distance. The problem of intermixing is not only related to ERW and horizontal designs but can also happen in vertical boreholes due to an insufficient displacement process. When the cement inside the workstring is displaced via another fluid, a so-called contact interface separates both liquids. However, contamination cannot be eliminated but only limited since no mechanical barrier separates both fluids. According to Durmaz et al. (2016), interface stability and efficiency depends on flow rate, pipe size, inclination, rheological parameters of the displacing and the displaced fluid and also the different densities and interfacial tension between the liquids. It is reported that during a "successful" displacing job, approx. 15% of the plug cement volume is contaminated by the displacing fluid, whereas the cement contamination can be up to 50% and more if the physical parameters of the displacing phase are not optimized (Durmaz et al. 2016).

4.1.1.3 Cement slurry induced losses

LC- cement plugs are designed to carry clogging material down the wellbore and seal loss zones to enable a safe drilling operation. The slurry itself should exhibit a low density in order to prevent further induced losses. Many operators add cenospheres to the slurry to achieve a light weight cement fraction. Putra et al. (2016) showed that there is a depth limitation where these cenospheres can be applied. If the downhole pressure exhibits a certain threshold, cenospheres can collapse and the application of highly crush-resistant material is necessary. The cenospheres can withstand a compressive strength of 3,000 psi (Goel et al. 2014), until they collapse (Figure 16). The consequence of collapsing is, that the density of the cement slurry increases which subsequently leads to a slurry induced lost circulation problem.

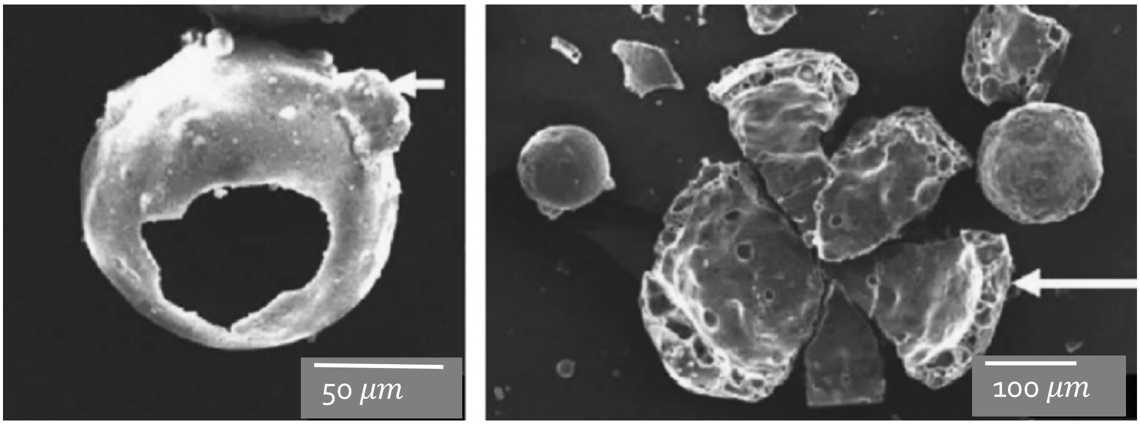


Figure 16: Hollow and crushed cenosphere
The left picture shows a hollow and the right a crushed cenosphere under compressive loading. The same happens to the cenospheres in the light weight LC cement if the downhole pressure exceeds a certain threshold. As a consequence, cement slurry density increases and induces further losses. (adapted from Goel et al. 2014)

4.1.1.4 Insufficient Strength Properties

Especially for kick-off plugs sufficient strength properties are important. If the cement system can resist less compressional strength than the formation to be drilled, the bit will not be guided into the right direction and the kick-off operation fails. Nelson and Guillot (2006) report that whipstock plugs should have a compressive strength between 5,000 to 7,000 psi (35 to 49 MPa). If a wrong kick-off point is selected, compressional strength of the lithology can be higher than the strength of the cement. As a consequence, the operator will never be able to sidetrack from the desired location because the cement will be drilled first. Temperature and workstring contamination also influence plug properties and strength characteristics. Their impact was already discussed before.

A widely industry related argument is, that densified slurries reduce settling of solids in the plug and hence create a more homogenous and strong kick-off base. Unfortunately increasing the plastic viscosity (by densification) will not stop solids settling, since gel strength (static) and yield point (dynamic) properties are primary settling controlling mechanism. Therefore adding e.g. coarse sand rather than silica flour (= additive for strength development → Chapter 3.4.1) will not harden the plug in contrast to the fact, that the relative big coarse sand particles are very hard to be kept in suspension and therefore promote solids settling (J. Heathman and Carpenter 1994). In addition, high viscous cement slurries are prone to contamination when the balanced workstring is removed from the slurry (see 4.1.1.2).

Another problem that is associated with HPHT wells is addressed by Al-Yami et al. (2008). The cement strength developed by the C-S-H gel of a conventional class G cement (see Chapter 3.2) is limited by 110°C (230°F). Beyond that temperature the C-H-S forms under a metamorphosis so-called alpha dicalcium silicate hydrate (α-C_2SH) which reduces the compressive strength of the plug. As a consequence, the ROP of the plug may be higher than the ROP of the formation to be drilled and the plug job has to be repeated. Al-Yami et al. (2008) suggests to reduce the lime to silica content by adding silica material as well as manganese oxide. The addition of silica will form a phase known as tobermorite (C_5S_6H) instead of α-C_2SH at temperatures above 110°C (230°F). The tobermorite structure as well as the manganese oxide will improve the strength properties at high temperatures. Furthermore, cast metal fibers or the addition of particulated rubber can help to improve the plug performance.

4.1.1.5 Early setting of cement slurry

To prevent early setting of cement slurries, normally retarders are added to the system. The exact quantity and quality evaluation of cement retarders is of highly importance since over-retarding can influence WOC time dramatically. Early setting problems are not only related to temperature effects (4.1.1.1) but also guided by the chlorides that are present in the make-up water or in the wellbore fluids. Mitchell et al. (2011) states, that all sodium, magnesium and calcium chlorides in seawater, used as make-up water on offshore operations, act as slurry accelerators. A misinterpretation of the chloride influence can cause severe job issues such as early slurry setting and a stuck workstring. Haidher (2008) describes the negative effect of wellbore brines under ultra- high temperature conditions, where the combination of high temperatures as well as chlorides and bromides in the brine promote the acceleration of the thickening time of the slurry. Again, early setting issues might be a consequence if this phenomenon is not taken into consideration.

Another HPHT problem, that is reported by Haidher (2008), is called thermal shock. Here, pre-flush and spacer fluid will be heated up by the formation as they leave the workstring. Ultimately not only these fluids but also the string will get hot when the liquids pass the outer passage of the tool (see also 2.4.1 and Figure 11 for plug job description). If the amount of these fluids is calculated too low, no further cold pre-flush and spacer are available that can cool down the formation and the string. When the cement slurry reaches the heated section, a thermal shock reaction can cause the BHCT to rise above the calculated value, leading in an early setting of the slurry before it is balanced in place.

4.1.1.6 Inadequate cement volumes

The right cement volume estimation is essential for a successful plug job, especially for kick-off plugs to ensure a stable and undamaged working base and a right departure height for the sidetrack. To avoid insufficient plugs, an excess cement volume is added in the forefront to the calculated slurry fraction. J. Heathman and Carpenter (1994) reported, that typically plug excess volumes range from 100% to 350% of estimated hole volume (compared to primary jobs where the excess volume is about 30% to 100%). However, it was also identified that during secondary cementing operations, fewer calliper logs are run because of time and cost reasons. Furthermore, operators just "added" some volume to the calculated one to go for a successful job. The consequence were too small volumes and failed plugs because of oversized and non-calipered boreholes. The right hole size should be estimated and verified primarily with logging data rather than just by guessing or relying on drilling reports. The additional time spend in logging will help to reduce contaminated cements, underrated hole sizes and slumped cement plugs (James F. Heathman et al. 1994) as well as decrease the chance of over-displacing issues of the cement.

4.1.2 Failure of removing workstring from the cement plug

4.1.2.1 Swabbing effects and over-displacement issues

Roye and Pickett (2014) describe the balanced plug method as the most common setting procedure. Here, several factors can influence cement contamination. Even if the plug was set under perfect balanced conditions, contamination can still occur. When the cement string is pulled out of the thick cement slurry, swabbing induced intermixing between the cement and the spacer/mud can lead to a plug with insufficient strength characteristics and a soft top (Marriott et al. 2006). J. Heathman and Carpenter (1994) report that swabbing induced contamination will be increased if highly thixotropic slurries are used. Such high viscous slurries and slurries that have already developed its gel strength will suffer from greater contamination since on the one hand such immobile cement will remain kind of static in the workstring (normally the cement is under-displaced to fill up the void space when the pipe is pulled out → see also Figure 11) and on the other hand the thick cement outside the workstring cannot move that quickly to fill up the space. As a result, mud enters the void and creates fluid pockets (Figure 17), where drilling action of these plugs is characterized by hard cement cuttings and a "soft" drilled plug body (J. Heathman and Carpenter 1994).

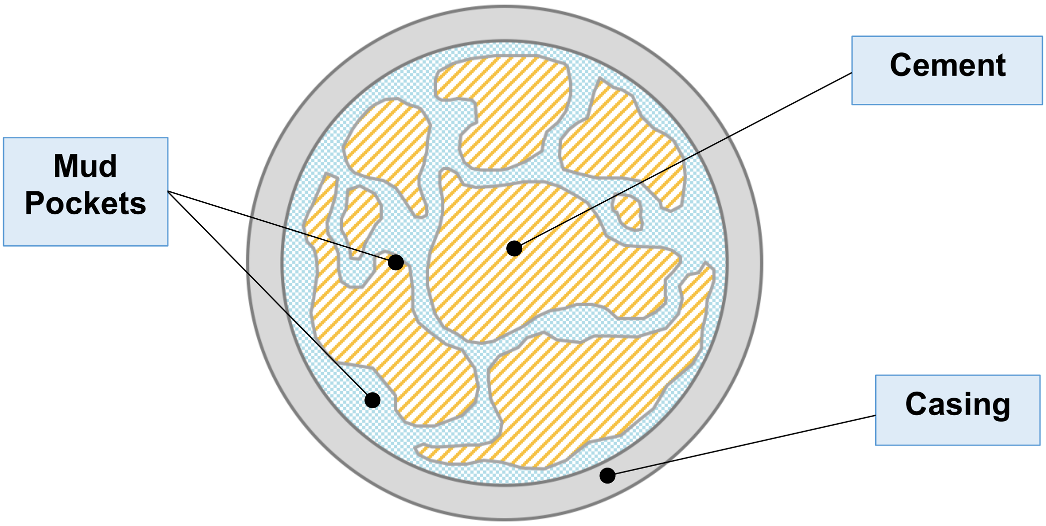


Figure 17: Non-homogenous cement plug
Contamination of cement plug caused by swabbing effects in combination with highly thixotropic slurries; cf. (J. Heathman and Carpenter (1994))

Beside swabbing effects, phenomenon such as over-displacement also suffer from contamination. Over-displacement is a result of wrong cement volume estimation (4.1.1.6) that can be caused by uncertainties in OH diameter, uncertain well conditions, wrong volume calculations or due to differences in pipe diameter if a DP-stringer combination is used. When a balanced plug is over-displaced, the cement level inside the workstring is less than the outside one (Nelson and Guillot 2006). If the string is pulled, all of the cement inside the string has left the pipe before the pipe itself has left the top of the balanced plug. As a consequence, the remaining steel volume is compensated by the less viscous and more mobile mud rather than by the cement.

4.1.2.2 Differential Sticking Problems at LC-Plug setting

Differential sticking is a common problem that is reported when a LC-plug is set across a weak formation. The sticking occurs because of the differential pressure between the mud column in the borehole and the formation liquids (Outmans 1958). To enable a safe drilling through a LC-formation, cement plugs can be set across the trouble shooting zone. Rogers and Poole (2012) report that the cement can be placed in two different ways. Either by bullheading cement down the wellbore or by balancing the plug across the loss zone. The first option result often in only partly isolated and covered zones. When drilling through zones that where healed with bullheaded cement, losses are often experienced again. The second option is to balance the plug. According to Marriott et al. (2006) best success is achieved if the drillstring is placed across the zone of interest. The problem is, that the loss of fluid into the wellbore can result in a differential pressure that sticks the workstring to the borehole wall. To enable a safe setting of a LC plug, the workstring should be kept always above the loss zone to avoid that the pipe gets differential stuck. The use of a sacrificial tubing (2.4.5) also increases the success of setting a LC plug.

4.1.3 Cement Plug Base Failures

Beside contamination effects, cement plug base failures and insufficient bonding between the plug and the system are major causes why plugs fail. Literature study shows that the oil and gas industry has identified these problems, but a precise classification was never executed. Since many cement plug operations fail because of missed plug base specifics or insufficient bonding characteristics, it is decided to extend the ordinary plug failure classification (4.1.1 and 4.1.2) by two additional groups. The first group deals with plug base failures:

Cement plugs like kick-off plugs must be set at a specific calculated point in the borehole to provide an appropriate starting point for further sidetracking operations. If the top of the plug is set too low or too high, sidetracking could be very challenging since on the one hand a pre-selected "soft" formation must be encountered and drilled to enable a kick-off from the original borehole and on the other hand a desired target (e.g. different reservoir layer) should be met by drilling a precise and pre-defined sidetrack trajectory. To meet the described objectives, a kick-off plug must be set across a competent plug base. Normally such a plug is placed off bottom in the wellbore, meaning that no solid, pre-existing structure is below the plug where the slurry can be placed on. Because the density difference between the cement and the wellbore fluids would be too high to place a plug successfully at the desired location, a unitary and firm system is needed between the slurry and the mud. To do so, either a mechanical bridge plug (Nelson and Guillot 2006) or a viscous and densified fluid is set below the point of interest. A proper selection of these auxiliary means is the base for a successful kick-off platform but also face a lot of problems that will be discussed now in more detail.

4.1.3.1 Incompetent plug base

As already stated, a precise selection of the right plug base is a key to a successful kick-off plug. Often wellbore or lithology specifics lead to a wrong decision for the right tool, resulting in incompetent and non-qualified plug bases and ultimately high costs and lost rig time. A bridge plug (Figure 18 a) is one option and represents a solid mechanical base that consequently separates the wellbore fluids from the slurry- if set properly. Nevertheless, such mechanical devices often contain different materials that can lead to problems when exposed to the wellbore environment. Chapman et al. (2008) reports, that elastomers of bridge plugs suffer from degradation by chemicals and temperature. In such cases, sealing efficiency can drop dramatically, especially at temperatures beyond 150°C (300°F). Furthermore, it is reported, that increased differential pressure across the bridge plug can lead the rubber elements to break down and cause severe issues for the retrieving process (e.g. if the bridge plug was used as a base for setting a test plug above; see also 2.3.7). Beside the technical malfunctions, availability, transportation costs, borehole specifics or a long lead time can additionally cause problems. As a cheap and quick alternative to a bride plug also viscous and densified fluids can be used as a cement base. The fluid can be mixed and produced without additional effort straight on the rig site and pumped ahead the cement slurry to the designated zone. Nevertheless, wrong density differences between the liquids and deviated wellbore characteristics can lead to a breakdown of the plug base and consequently to slumped and contaminated slurries. These issues are discussed in more detail in 4.1.3.2 and 4.1.3.3. Another device that is used by the oil and gas industry for kick-off operations is a so called mechanical whipstock (Figure 18 b) that can be placed in the wellbore either cemented in place or with inflatable packers.

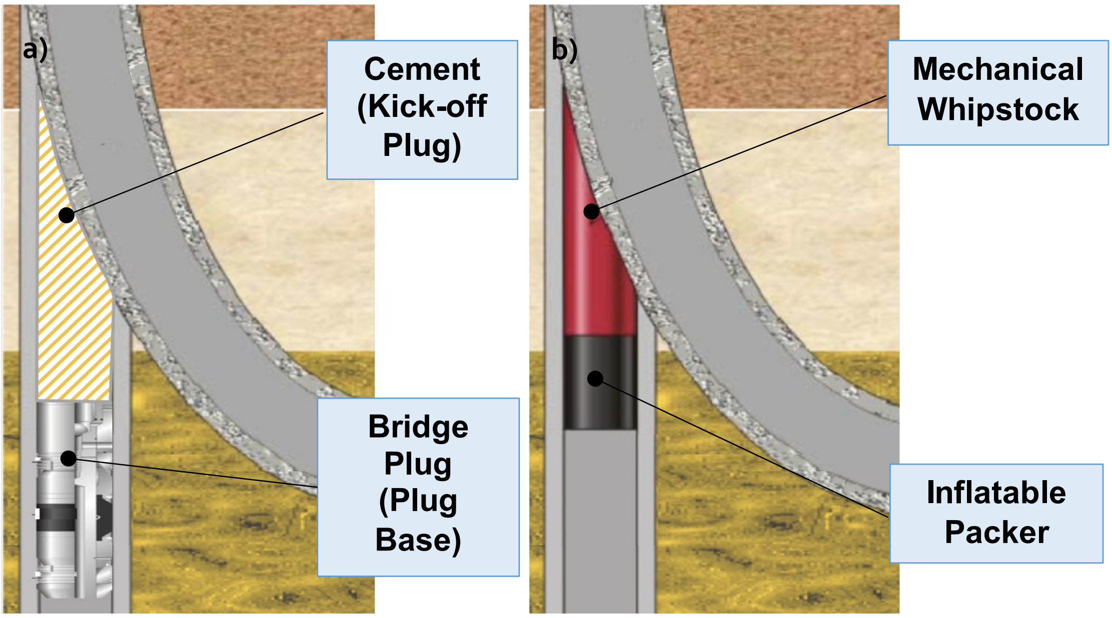


Figure 18: Bridge plug cement combination (a) and mechanical whipstock (b) as kick-off plugs
The bridge plug in (a) was used as a cement plug base, whereas in (b) a pre- manufactured whipstock with inflatable packers was run (c.f. Broussard, Templeton, and Travis (2009)).

Although it seems more convenient using a mechanical whipstock rather than a cement plug for kick-off operations, several issues related to whipstock jobs were reported. Broussard, Templeton, and Travis (2009) stated, that mechanical whipstocks with inflatable packers often fail during setting operations. Partial inflation because of malfunction or wrong pump selection resulted in unset whipstocks. Furthermore, fluid hammer effects initiated by fluctuations and too high flow rates caused the closing mechanism of the packer to trigger, although it was just partly filled. Beside the described effects, whipstocks were not holding properly especially when the tool was set in washed out zones. This had often the consequence, that the tool was falling into the wellbore and the kick-off had to be executed by setting a cement plug.

In general it can be said that any mechanical plug base solution should be preferred if the plug is set across a large hole size (Nelson and Guillot 2006), whereas in smaller wellbore diameters and out of gauge holes, a densified and viscous fluid base should be chosen.

4.1.3.2 Insufficient density equilibrium

Cement plugs that are set above a densified fluid often suffer from slumping effects. Slumping means, that the slurry falls through the viscous plug base and causes insufficient and incomplete plugs. Beirute (1978) studied this problem and described the slumping process with water and oil phases. If a water phase is dropped onto an oil phase such as diesel, the water will flow downwards and slump through the diesel because of the density difference between these two fluids, displacing the diesel at the same time upwards. If the density between the slurry and the mud or the spacer is too high, the same happens downhole where the cement falls through the base fluid, displacing at the same time the lower dense fluid upwards, causing severe contamination and damage (Figure 19).

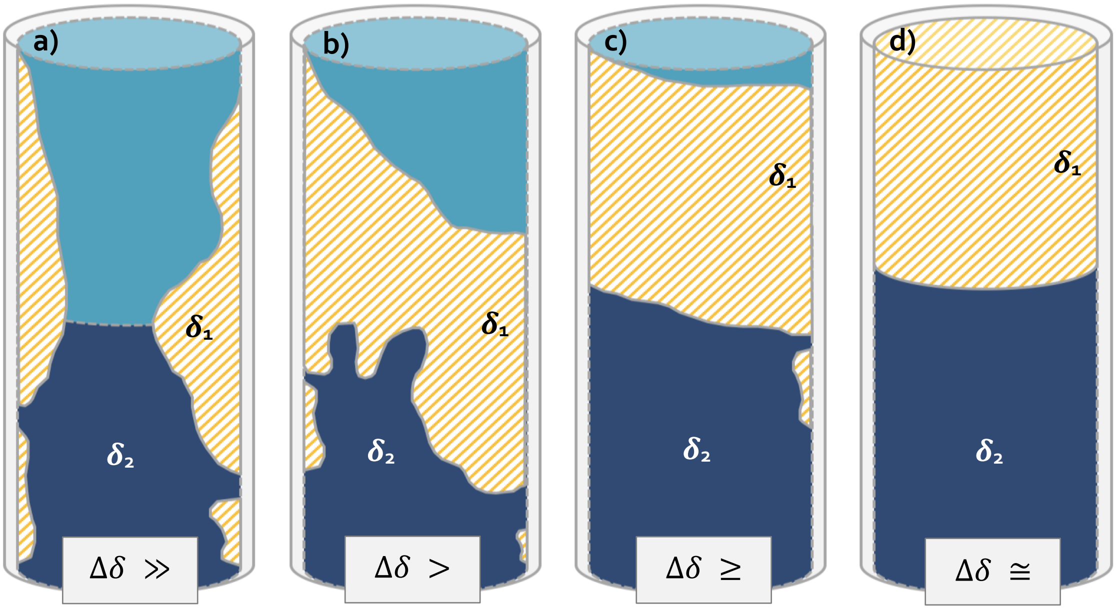


Figure 19: Contamination damage caused by density difference between cement and plug base
Decreasing density difference between plug base and cement will increase the likelihood of a good and undamaged plug. Severe damaged and no usable plug (a), damaged and unusable plug (b), small damaged but usable plug (c) and perfect set plug (d) in a vertical wellbore.

Contamination of cement slurries because of too high-density differences between the various fractions can influence the strength development of the plug negatively. Smith (1984) conducted several experiments, to explore the manipulation of the density difference on the contamination of cement plugs. It was found out that if a heavy cement was balanced above a lighter plug base, downward movement of the cement will definitely happen. Smith showed, that the maximum density difference between the cement and the plug base fluid should not exceed 2.8 lb/gal (335 kg/m^3), whereas J. Heathman and Carpenter (1994) suggest that the difference should be kept within 0.2 to 0.5 lb/gal (24 kg/m^3 to 60 kg/m^3). However, if a diverter tool (closed ended pipe with exit holes drilled at the side walls to allow a lateral and upward movement of the fluids in the annulus) is used to place the fluids, improvements could be seen. In this case, Smith found out that the maximum density difference can be shifted up to 6.8 lb/gal (815 kg/m^3).

Crawshaw and Frigaard (1999) executed several experiments, simulating plug base problems elicited by density differences and subsequent cement contamination in deviated wellbores. They extended the deviated flow model developed by J.F. Heathman (1996) where a sliding and extrusion flow pattern between the heavier slumping cement and the upward moving lighter plug base fluid was described. Crawshaw and Frigaard divided the flow region into three parts that consists of a long axial exchange flow region where the motion of the cement and the base fluid is almost parallel with the axis of the borehole, an upper and lower transition zone with complex flow specifics and the upper and lower undisturbed zone where no contamination has happened (Figure 20).

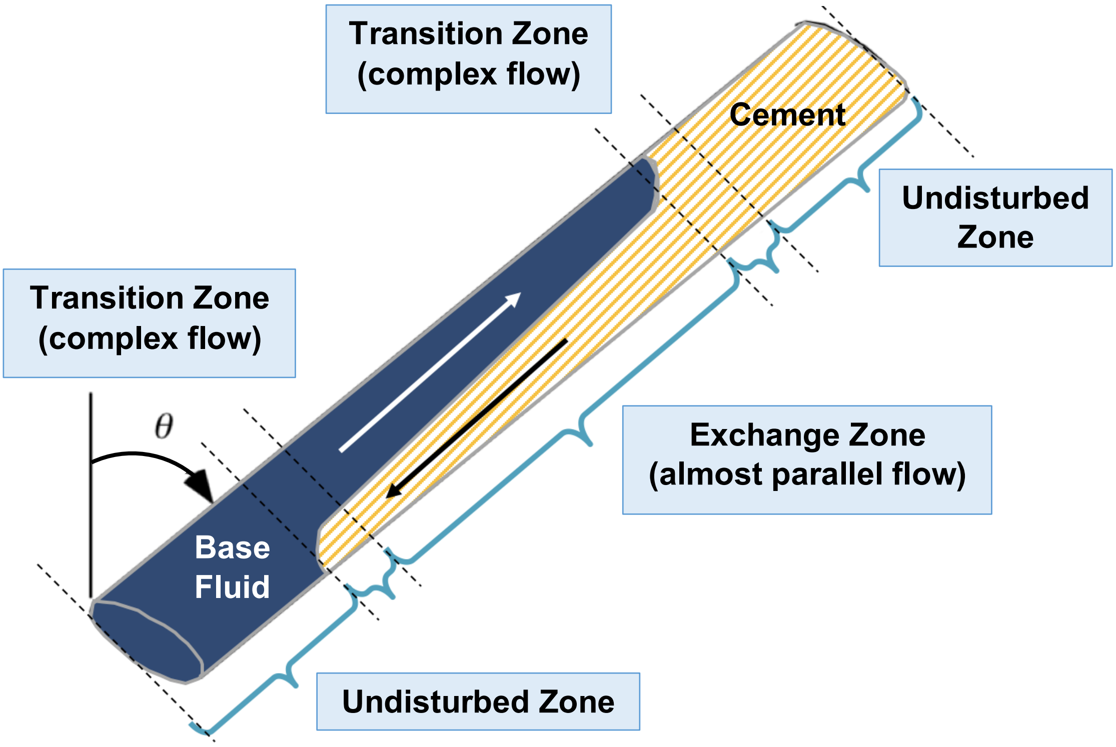


Figure 20: Flow zones in a deviated borehole caused by the presence of different dense fluids
Because of the different densities of the cement and the underlying plug base fluid, three flow zones occur. Contamination of the slumping cement is the consequence (c.f. Crawshaw and Frigaard 1999)

Crawshaw and Frigaard applied to the in Figure 20 described set-up different pipe diameters, changing inclination and various density differences between the cement and the base fluid (it has to be mentioned that the fluids were chosen to be Bingham ones, since Bingham fluids form a yield stress and will not flow until a specific stress is applied). A result of their experiments was that the stability of the interface between the two fluids (a stabile interface means that no intermixing happens) is governed by the inclination angle θ and the yield stresses of the base fluid and the cement respectively. Furthermore, they came up with a yield stress distribution plot that describes the stability limit of the interface (Figure 21). Any base fluid to cement yield stress distribution located on the upper right side of the plot will indicate stabile conditions and no slumping. Concluding, it can be said that the contamination of cement in deviated wellbores is strongly influenced by the inclination angle as well as the density difference and hence the yield stress distribution of the fluids. J.F. Heathman (1996) performed vertical plug setting experiments and observed that the slurry did not slump through the plug base fluid as it was recognized in deviated and horizontal ones but winded in a clockwise, spiral flow pattern down the wellbore, forming a double helix of cement with sometimes a usable cap on top.

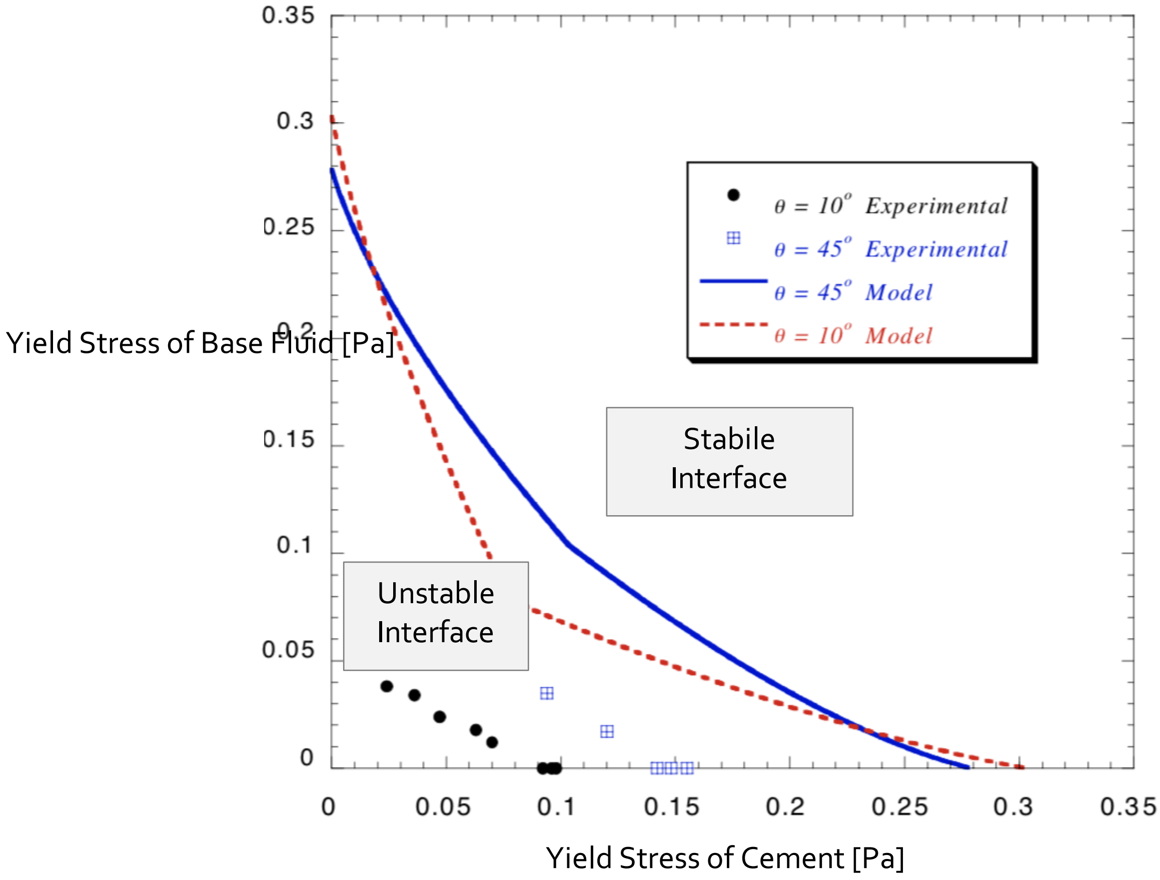


Figure 21: Yield stress distribution plot for assessing the stability of the fluid interface in deviated wellbores

If the cement to base fluid yield stress distribution is located on the upper right side of the curves, a stable interface can be assumed. The experiments were executed for two different inclination angles (10° and 45°). It is mentioned by the authors of the paper, that the experiments were conducted under laboratory conditions with no influence of pressure and temperature (c.f. Crawshaw and Frigaard 1999).

4.1.3.3 Settling issues- Boycott effect

A phenomenon that can be observed in deviated wellbores is the so-called Boycott effect (Figure 22). It is a sedimentation process of particles that settle down on the upward facing wall of the borehole. This process was first described by Mr. Boycott in 1920. He found out, that oxalated blood corpuscles sediment faster in deviated pipes than in vertical ones. The settling particles (higher density) reaches first the upward facing side of the lower glass pipe wall and formed there a concentrated liquid, while leaving a clear liquid (lower density) above them (Xu and Michaelides 2005). The impact of the Boycott effect on the liquids and the behaviour of the liquids are similar to the processes described in 4.1.3.2 however, here particle settling is responsible for the fluid movement and not a density difference. J. Heathman and Carpenter (1994) describe the Boycott effect as a problem where the heavy sediment layer on the lower side of the wellbore slides down very rapidly promoting at the same time the upward flowing of the now more buoyant base fluid. As a result, contamination of the cement slurry happens resulting in the formation of stratified layers (similar to Figure 17). Ultimately kick-off plugs that suffer from Boycott effect cannot form sufficient strength and fail if being penetrated by the bit. However, Calvert, Heathman, and Griffith (1995) performed several experiments to study the influence of the Boycott effect on the slurry properties. They found out, that the effect was only obvious at thin cement slurries, whereas thick slurries were influenced by the density difference between the participating fluids and behaved as described in 4.1.3.2.

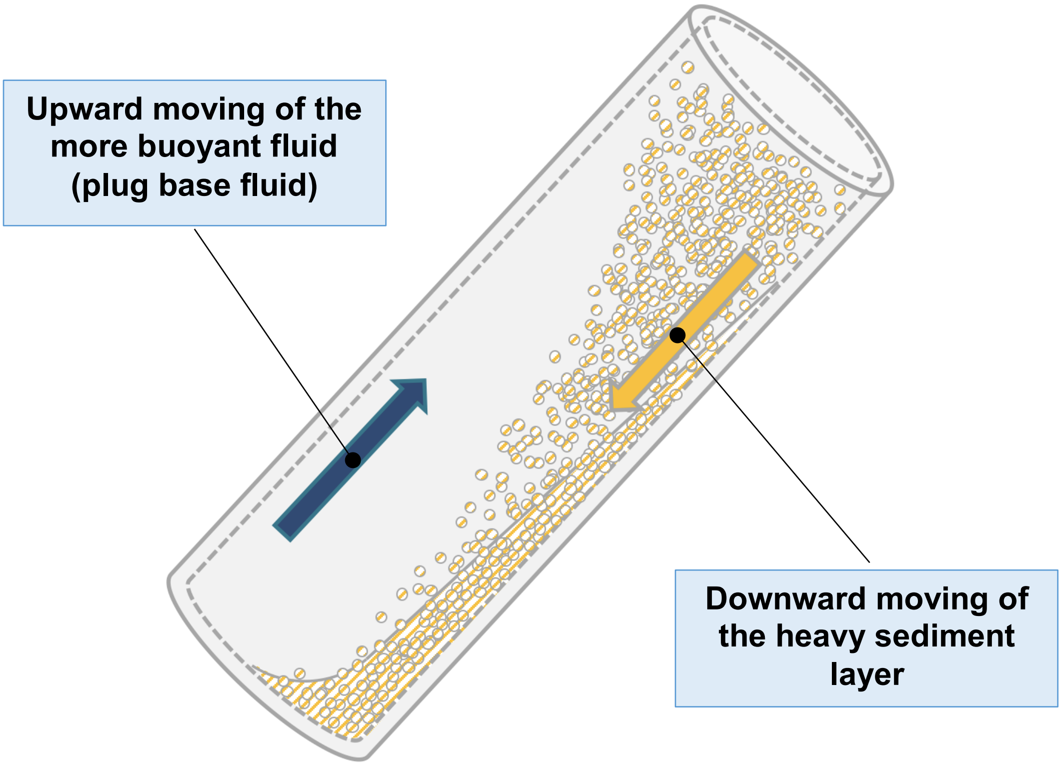


Figure 22: Boycott effect in deviated wellbores
The Boycott effect influences only thin cement slurries, where the sediments settle on the upward-facing side of the lower borehole wall, creating there a heavy layer that slides down. Ultimately more buoyant plug base fluid flows upward and causes cement damage.

4.1.4 Bonding failures between cement plug and system

The fourth group of technical plug issues deals with bonding failures between the set cement plug and its environment. The opinion of the author of this thesis is, that bonding issues are a common problem why plugs fail but are often not mentioned or just discussed briefly in many of the papers. Especially for kick-off plugs but also for abandonment plugs, an adequate bonding caused by adequate mud removal is essential for the success of a plug operation. In the following, the most prominent problems are discussed in more detail:

4.1.4.1 Insufficient annular velocity and erodibility

Insufficient mud removal is one of the major issues, why a bad bonding between the cement and the casing or OH section is developed. A bad bonding can result in either gas migration and untight abandonment plugs or massive problems during kick-off operations (see 4.1.4.2). Research by T. R. Smith (1989) has shown, that insufficient annular velocities are a major contributor to insufficient mud removal and hence failed cement plug operations. Smith showed, that high annular velocities provide best displacement results regardless which kind of flow regime they applied. It could be proven, that a velocity of 80 m/min (263 ft/min) should be obtained to achieve best mud removal results (Figure 23).

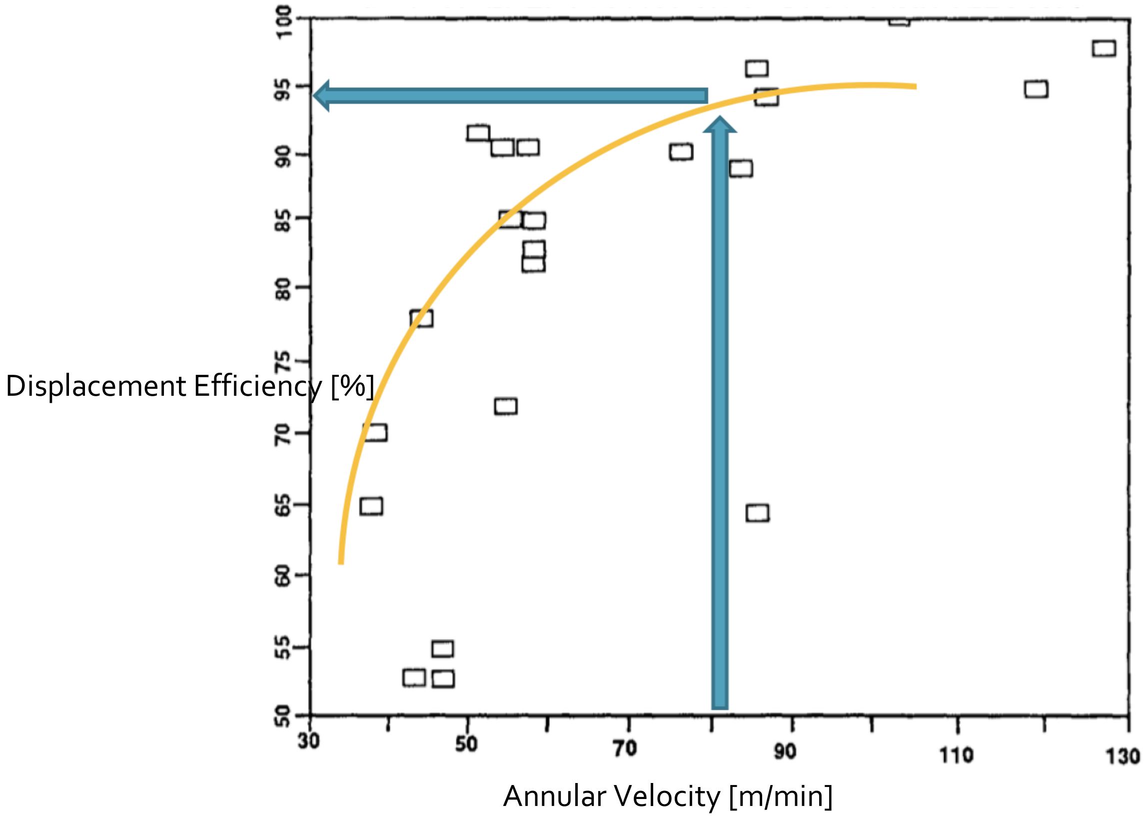


Figure 23: Annular velocity versus displacement efficiency of mud

It can be seen, that an annular velocity of approx. 80m/min (263 ft/min) is an optimal value for efficient mud removal. The cleaner the borehole, the better the bonding between the system and the cement plug (c.f. T. R. Smith 1989)

Mud removal issues can be increased if a plug is set in a highly deviated or horizontal wellbore. Similar to cuttings removal problems in such boreholes, mud removal can also be challenging, since non uniform flow regimes and different flow velocities are a common problem that can be observed in such wellbores (Farahani, Brandl, and Durachman 2014). A pre-job velocity simulation can help to assess a flow distribution that increases the chance of good bonding due to sufficient mud removal. Beside the efficiency of annular velocity increase on mud removal, K. M. Ravi, Beirute, and Covington (1992) introduced the term erodibility of drilling mud. They state that if the erodibility of the mud is known, shear stress of the spacer needed to displace the mud and the cake from the wellbore can be calculated. Furthermore, if the wellbore diameter is known, spacer rheology and flow rate can be assessed to meet the required shear stress in order to remove as much mud and cake as possible.

4.1.4.2 Plug rotation issues

Plug rotation problems are strongly linked to inadequate mud removal before the plug is set. Rotation of plugs mainly affect kick-off plugs and can cause severe issues. Even if all cementation problems (e.g. contamination, fluid pockets, plug base instability or strength issues) could be mitigated and on the first sight, a "perfect" plug was set, troubles can occur when the operator begins to kick-off the wellbore. James F. Heathman et al. (1994) reports of kick-off plugs that could not promote the drill bit to change direction and sidetrack from the wellbore. Although all requirements for a successful plug where met, deficient mud removal caused the plug to fail. As a consequence, the plug began to move and rotate because of the absence of a sufficient binding between the borehole and the cement when impact force of the drill bit was applied. To prevent such rotational induced issues, an adequate removal of gelled mud and mud cake is important. As already stated by T. R. Smith (1989), James F. Heathman et al. (1994) also suggests to apply annular velocities between 40 m/min (120 ft/min) to 80 m/min (approx. 263 ft/min) to avoid layers of gelled mud that promote plug rotation.

4.1.4.3 Insufficient spacer design

A proper spacer design is important for setting a plug successfully. Operators pay a lot of attention to spacer design during primary cementing operations but often fail to meet the requirements for secondary cementing jobs. During secondary operation, inadequate spacer design could be more severe and cause a higher number of problems, since the volumes of cement that the operator deals with are much smaller and little variations result in big consequences. Inadequate mud removal can not only lead to cement contamination (4.1.3) but also causes a bad bonding between the wellbore and the slurry. Therefore, it is important to design a spacer that meets all the objectives and mesh with all other fluids present at the job. The spacer fraction is normally pumped ahead and after the slurry fluid. Incompatible spacers can inhibit mud removal (Ferg et al. 2011).

Another issue that is reported with insufficient spacer design is a reduced bonding between the cement and the surface, in case a synthetic based mud (SBM) was used. The oil in the SBM and the water in the cement slurry are immiscible. In case, that a cement plug is set in a SBM system, a special spacer must be designed in order to prohibit bonding issues between the plug and the surface. To water wet the former SBM system, so-called surface-active agents or surfactants are added to the spacer.

Surfactants are components that reduce the interfacial tension between two liquids or a liquid and a surface and consist of a hydrophobic tail (has affinity to oil) and a hydrophilic head (has affinity to water) that allow the water wetting of the surface and exhibit a proper cement bonding and hydration (Pereira et al. 2017). SBM not only influence the bonding efficiency negatively, but also affect the rheology (viscosity) and compressive strength characteristics of the slurry and ultimately the overall contamination. To reduce all issues related with SBM, a sufficient spacer design must be developed and executed in a so-called spacer train, that consists out of different spacer batches with various chemical additives in order to maintain a water wet system for the plug, keep contamination on a minimum and provide a clean area for a good bonding. Farahani, Brandl, and Durachman (2014) recommend of a proper selection of the surfactants since wrong surfactant volumes or chemicals can negatively affect the properties at the mud/spacer interface, destabilize sensitive formations or not effectively water wet the surfaces.

4.2 Root cause analysis

In chapter 4.1, most frequent kick-off and LC plug challenges were discussed. To do so, more than 35 different papers were analysed and rated. The papers compromised various challenges, new inventions and best practice methods as well as studies and failure analysis, covering most prominent drilling locations in the world such as the Gulf of Mexico, Norway, Middle East and India. Based on these papers and articles, so-called failure characterization groups were implemented (4.1.1, 4.1.2, 4.1.3 and 4.1.4). The following chapter covers a root cause analysis of the individual failure groups and their corresponding results. It was decided to evaluate the individual issues that cause LC plugs but mainly kick-off plugs to fail. On the one hand, this assessment should give one an overview and a summary of chapter 4.1, and on the other hand this evaluation is conducted to address the most prominent influencing factors that lead cement plugs to fail. Table 5 is a summary of the failure group evaluation. It is decided to split the table into three categories, called root causes, results and consequences (Figure 24).

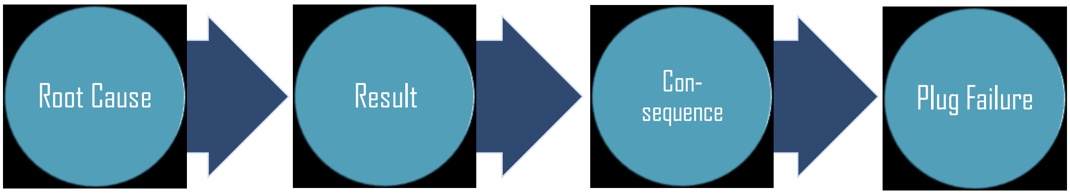


Figure 24: Root cause to plug failure scheme

The root causes describe the various parameters that are the primary cause for plugs to fail. If one of the root causes is ignored or misinterpreted during design phase, ultimately a result follows. The result is the influence of the root cause on the system and triggers consequences that lead the cement plug to fail in the end.

Root cause analysis

#	Root Cause	Result	Consequence
1	Insufficient temperature estimation	Over- retarding	Cement contamination Increase in WOC Reduced strength properties
2	Influence of low seawater temperature (especially in deep water regions)	Wrong BHCT	Reduced strength properties Increase in WOC
3	Intermixing of fluids in workstring	Insufficient interface stability between fluids	Cement contamination
4	Insufficient crushing resistance of LC material	Collapsing of cenospheres	Slurry induced losses
5	Wrong selection of Kick-off point (formation strength higher than kick-off plug strength)	Insufficient compressive strength design of plug	Problems or unable to kick off
6	Underestimated BHT (especially in HPHT wells)	Insufficient compressive strength design of plug	Problems or unable to kick off
7	Wrong assessment of chloride influence	Early setting of slurry	Cement contamination Stuck workstring
8	Insufficient cooling of formation and workstring	Thermal shock	Cement contamination Stuck workstring
9	Wrong hole size estimation	Inadequate cement volume	Cement contamination Over-displacing of slurry
10	Pulling workstring too fast from thick slurry	Swabbing effect	Cement contamination

11	Loss of fluid into permeable formation	Differential pressure	Differential sticking of workstring
12	Incorrect selected type of plug base for present well conditions	Failure of plug base	Cement contamination
13	Insufficient density equilibrium between cement and plug base (influence only thick slurry systems)	Helical slumping of cement in vertical wellbores	Cement contamination
			Reduced strength properties
		Sliding and extrusion flow in deviated wellbores	Cement contamination
			Reduced strength properties
14	Boycott Effect (influence only thin slurry systems)	Sedimentation of slurry particles	Cement contamination
			Reduced strength properties
15	Inadequate spacer design and mud removal problems at borehole wall	Insufficient bonding	Bonding problems/ unable to kick off
		Plug rotation	Bonding problems/ unable to kick off
		Insufficient separation between mud and cement	Cement contamination
		Problems to water wet the system if SBM was used	Cement contamination
			Reduced strength properties
			Bonding problems/ unable to kick off

Table 5: Summary of the failure group evaluation.

The table shows a summary of the assessment of the individual challenges that lead to kick-off and LC plug failures of chapter 4.1. One can see, that the table is split into root causes- addressing the parameters that establish plug failures, results- showing the direct influence of the root causes on the system and the consequences that finally lead to plug failures.

In total, 15 different root causes are evaluated that ultimately lead to failures of the cement plugs. The individual root causes are a representative industry average and represent the most frequent issues that operators deal with. There are also additional individual challenges that would need to be analysed, however these issues are limited to local circumstances like specific geological conditions or other anomalies that cannot be covered in this thesis.

For a better understanding of the plug failure consequences and for an assessment of the most prominent influencing factors, a detailed listing is conducted. Figure 25 shows the result of the assessment of the individual consequences.

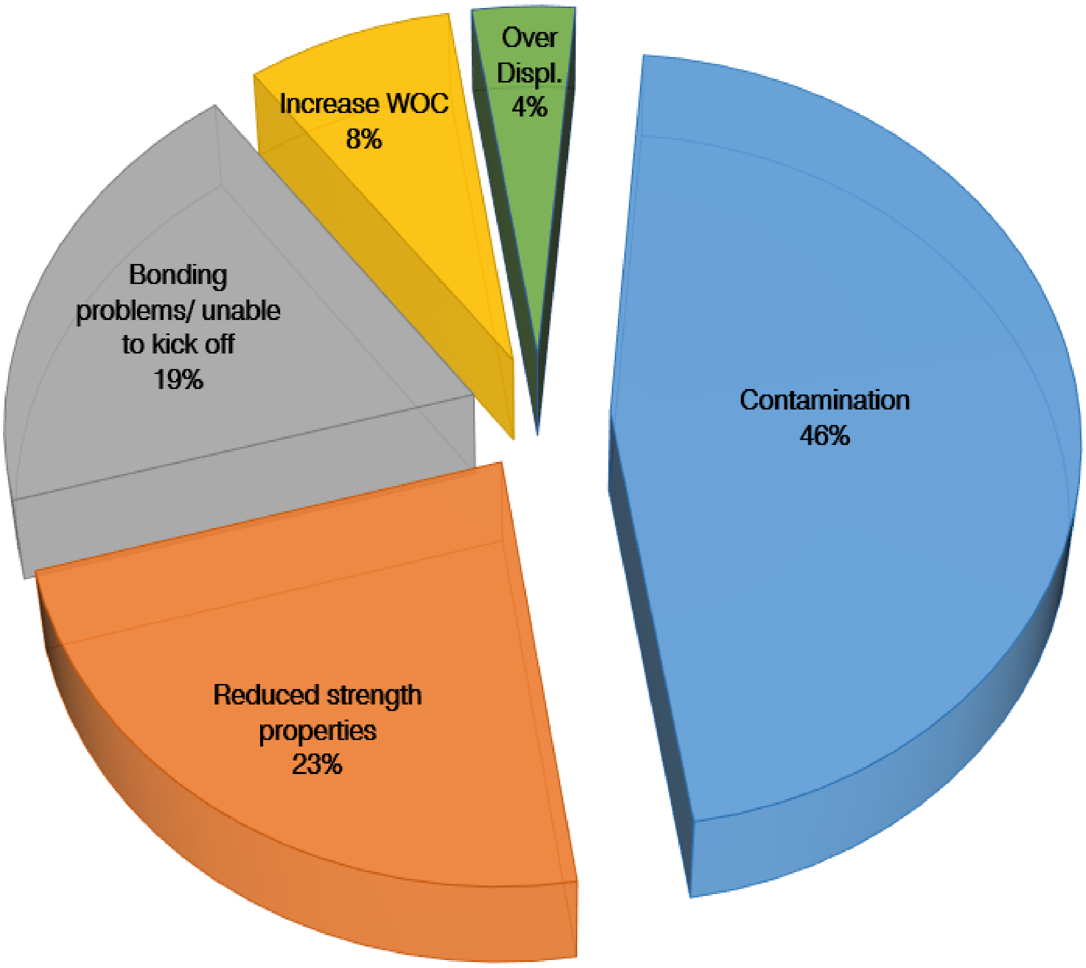


Figure 25: Individual consequences implemented by different root causes and how much they contribute to kick-off plug failures

The assessment of the individual failure groups shows, that 46 % of kick-off plug failures are caused by cement contamination. This indicates, that contamination is most prominent failure mechanism and in fact it is a challenge that operators often deal with. It has to be mentioned, that the results presented in Figure 25 are kind of dynamic, meaning that one parameter can influence another one and vice versa. For example, contamination of the slurry can lead to reduced strength properties of the kick-off plug and hence provide massive problems if the wellbore has to be side-tracked. If one also implicates reduced cement strength issues, it can be concluded that only these two parameters redound to approximately 70% of kick-off plug challenges.

Contamination is a wide spread issue and demands most research and improvement. This is also, because cement contamination is more complex than it seems. Many influencing factors like temperature gradients and cooling mechanism, varying hole sizes, too fast pulling rate, insufficient density equilibrium or inadequate mud removal account for contamination and must therefore be considered when planning a cement plug job. Furthermore, many of these factors are regulated on their part by other driving mechanism such as rheology, velocity distributions or different chemical and physical parameters. If cement contamination issues and plug strength challenges are mitigated or reduced, the probability of setting a cement plug at first attempt will increase comparably. The results of this chapter also provide a basis for the implementation of the data analysis tool described in Chapter 5. Also, laboratory simulations and tests will be optimized and realized based on the findings and outcomes of this chapter.

4.3 Economic challenges

The following chapter discusses the economic impact of cement plug jobs issues on the overall wellbore costs. As already discussed in the chapters above, cement plugs are set for a various number of reasons, but the majority of all set plugs are for kick-off operations, lost circulation curing or P&A of wellbores.

Beside the technical challenges, companies focus even more on the economic impact of a oil and gas operation and try to keep the costs on a minimum. Setting cement plugs such as kick-off plugs are often dedicated as a side event that is only executed to provide the base for further drilling activities. Therefore, operators spend less time in planning and designing plug operations, resulting in massive non-productive time (NPT) and additional rig costs. Crawshaw and Frigaard (1999) stated, that it has become more a rule than an exception to set several plugs before the operator can successfully sidetrack a wellbore. A failure study, executed by Halliburton in 2016 showed, that plug issues have become the fifth most important factor, which influences NPT and consequently overall rig costs negatively (Figure 26). Oil price shocks such as experienced in 2014-2017 keep operators nervous and cost optimization and efficiency have become the new driver for any new oil and gas project. According to Cochener (2010) "efficiency" is declared as a metric of productive output, for a given set of inputs. To measure, rate and enhance the term efficiency, various numbers of key performance indicators (KPIs) are used by the operators (Souza, Sasso, and Munoz 2017):

- Meters drilled per hour
- Meters drilled per rig
- Costs/m drilled
- Drilling days to planned TD
- Number of wells drilled per rig
- Number of uneconomic wells drilled (success vs. dry hole)
- Additional reserves added per well
- Additional reserves added per rig
- Productivity per well

- Energy consumption

Focusing on cement plugs, issues can influence the efficiency by manipulating the overall drilling days to total depth and hence the project costs/m as well as number of meters drilled.

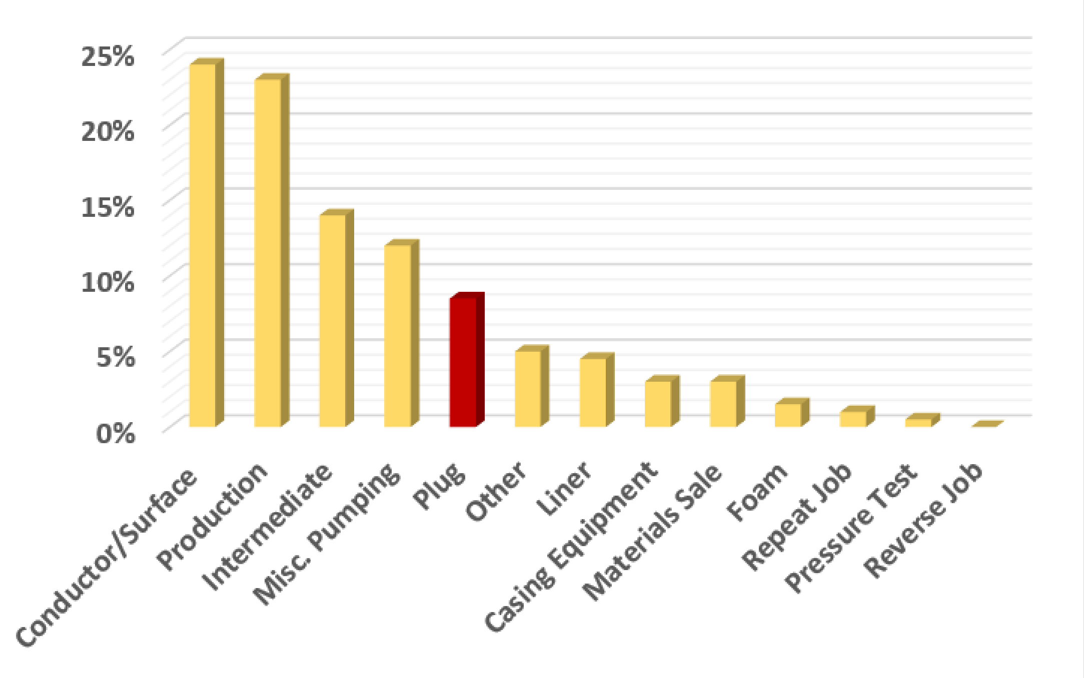


Figure 26: Hours of NPT spend on drilling issues
According to the study of Halliburton (2016) plug job issues have become the fifth most important influencing factor on hours spent on NPT. Compared to the small volumes and simple equipment that is used for setting cement plugs, such an influencing factor is impressive. It should be noted, that plug issues contribute more on NPT than liner or casing equipment failures (adapted from Souza, Sasso, and Munoz (2017), study was executed by Halliburton 2016).

J. Heathman and Carpenter (1994) showed, that the industry average for kick-off plugs are 2.4 attempts per successful kick-off whereas in some regions like the Gulf coast 2 to 5 attempts were needed until an operator could successfully sidetrack a wellbore. Figure 27 shows the costs per attempted kick-off for south Louisiana and Gulf of Mexico wells assessed in 1994 by J. Heathman and Carpenter. The term "OP" means that the plug operation was executed by the operator and the term "TK" means that the plug was set in a turnkey contract. It can be clearly seen, that none of these wells kicked off successfully at the first attempt. The minimum were three attempts until a sidetrack could be drilled. The possible prospects and reasons why all of these plugs failed to be set successfully at the first attempt are discussed in detail in Chapter 4.1 and analysed in Chapter 4.2, but is shows how much theoretical savings potential a first attempt kick-off has. If one transfers the numbers to today's economic situation, focussing thereby on the volatile oil market, retrenchment potentials are way higher since overall costs and expenditures increased dramatically the last decades.

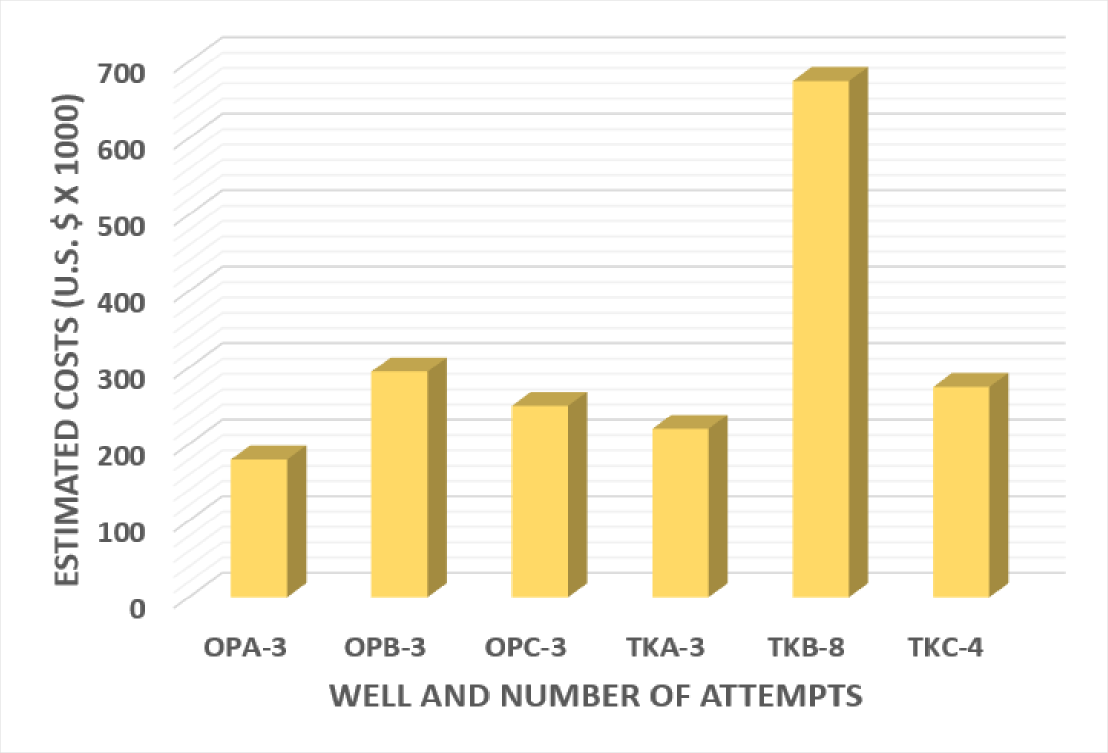


Figure 27: Estimated costs per attempted kick-off operation for south Louisiana and Gulf of Mexico wellbores

The diagram shows the estimated costs per attempted kick-off including rig time and cementing work. None of these wells successfully kicked off on the first attempt. It should be noted, that well TKB-8 had massive problems and it took the crew 8 attempts until a sidetrack operation could be executed. OP= Operator controlled; TK= Turnkey controlled; the number indicates the number of attempts needed for sidetracking successfully (c.f. J. Heathman and Carpenter 1994).

Today, planned time for setting cement plugs decreased dramatically also because of increased daily rig rates, crew and material costs. If a wellbore issue such as a fish or massive losses suddenly occurs, operator and service companies have to react and act fast in order to decrease downtime. As a consequence, oil and gas companies should have contingency plans available that exactly tell the crew what to do in case that losses or sidetracking have to be managed with cement. Decision trees which include threshold values and critical job events, evaluated by experiments or experiences, should be available on the site. By a quick look at the most influencing parameters and by comparison with the actual well delivered data, many plug job issues can be avoided in the forefront. Furthermore, a precise pre-job planning for potential kick-off jobs (such as location definition) and loss curing operations can mitigate over-hasty decisions.

Review has shown, that the average number of attempts needed to sidetrack a wellbore successfully is still at 2.4 (Farahani, Brandl, and Durachman 2014) today. Especially time required to WOC is often underestimated by the operators, also because WOC is often referred as NPT and therefore cost driving. Farahani, Brandl, and Durachman (2014) suggest a minimum WOC time of 18 hours before the plug should be tagged the first time. If the plug can be circulated through it is recommended to wait another 6 hours, meaning a total waiting time of 24 hours. Time where money is spend without deepening the well, but time that is necessary to allow the cement to form its characteristics. If plugs are drilled too early, regardless if it is a kick-off plug or LC plug, subsequent damage will happen. Hudson, Sones, and Eulberg (2015) report from plug failures that provoke more than 1,000 hours of lost time and USD 20 Million every year, also because the operators could not meet the specific requirements, including insufficient WOC. As a consequence, plug jobs have to be repeated several times. Figure 28 shows the number of plug jobs versus days spent on performing the jobs. The diagram represents statistical assessed job attempts until a well is kicked off successfully. It shows that theoretically maximal four attempts are needed to sidetrack a wellbore resulting in 12 days of rig time. If a plug was is perfectly, only one day will be spend for performing the job and WOC.

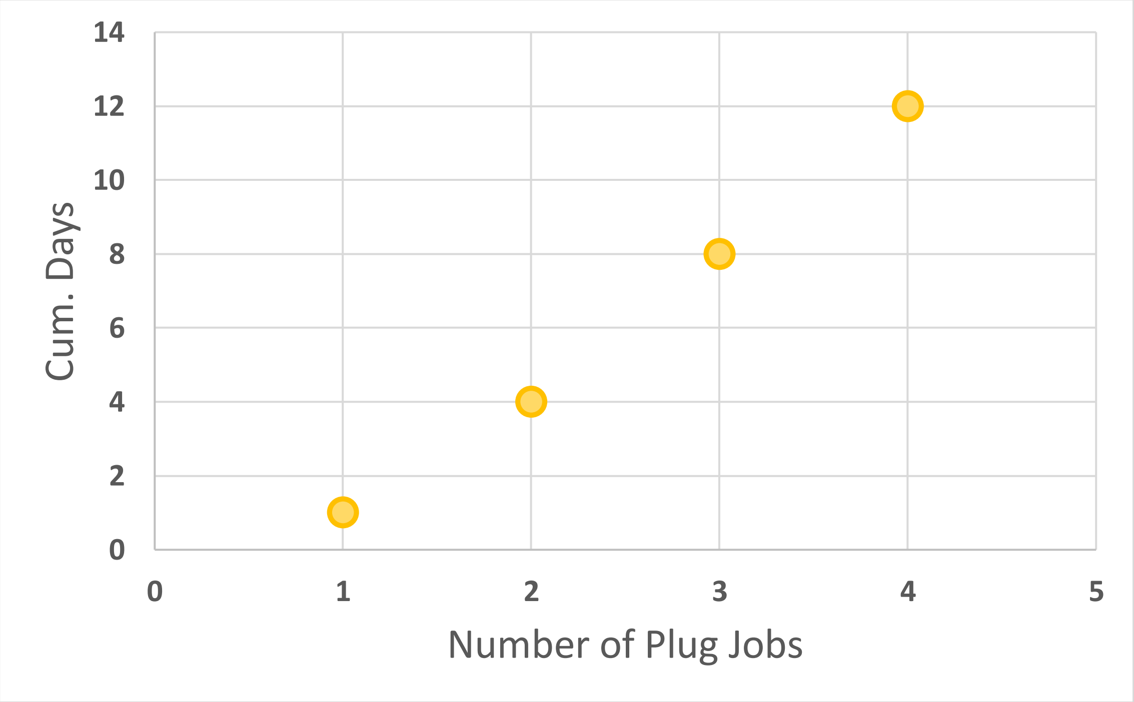


Figure 28: Number of plugs attempts versus cumulative days
The diagram shows the statistical evaluated number of plug attempts needed to sidetrack a wellbore versus the cumulative days spend on kicking off from the borehole. Theoretically a time delay of 11 days (in case that four attempts are needed) compared to a first attempt sidetrack can occur, resulting in massive cost increase (adapted from Rogers and Poole 2012).

Today, companies focus on more challenging and problem facing areas. Deep- water regions, ERW, long horizontal sections or SBM systems address completely new issues and make it more complicated to set a successful cement plug. Rig rents in deep-water regions can be as high as USD 45,000/hr (USD 1,080,000/ day) (Pereira et al. 2017). If a kick-off plug has to be set four times because of a cement error or improper job planning, NPT costs can increase up to USD 13 Million for a single kick-off operation. This emphasizes the importance of new technologies and strategies for cement plug jobs. Especially WOC consumes most of the time. New engineered cement recipes allow an early strength development by applying non-conventional material such as Micro silica, Metakoalin, Ground Granulated Blast Furnace Slag (GGBS) or Ceramic Microspheres. These cements decrease the time for WOC from 18-24 hours to 12 hours and ultimately saving rig time and costs (Banerjee et al. 2009).

Furthermore, cement plugs- if set successfully, can also be used to save rig costs. Compared to whipstock devices that are also used for kick-off operations, cement plugs can enhance the success rate and minimize costs and expenditures. Hussain et al. (2016) reports, that cement plugs are preferred over whipstock plugs since whipstock operations are very sensitive against out of gauge holes, can fall down the wellbore, need additional trips for window milling and possible polishing runs (consume additional time and hence costs) and limit the operator in applicability if only a narrow sidetrack escape window is available.

Chapter 5 Development of the Data Analysis Tool

The development and verification of a data analysis tool is the main part of this master thesis. The purpose of this program is the invention of an easy applicable tool, that supports any engineer in designing cement plugs. The data analysis tool can be described as a decision tree-based software that allows a quick scan of input variables, to check if the planned design parameters would theoretically support the success of setting a cement plug on the first attempt. In a first step, the analysis tool can be used to design and simulate kick-off plugs, but the structure of the tree is chosen in a way, that small changes allow the application on lost circulation- and plugging and abandonment plugs. The described adaption is not part of this master thesis but can be put into practice at a later stage.

5.1 Basic principles

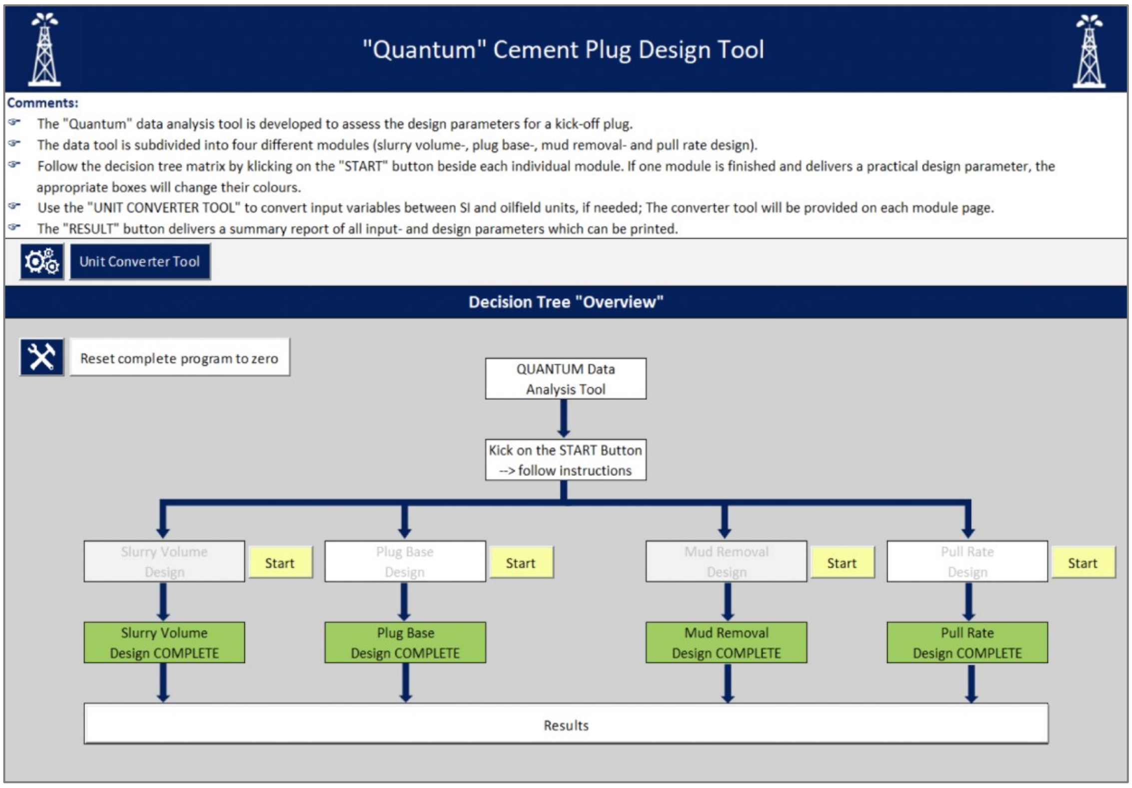
As already described in chapter 4.1, many industry related challenges and issues cause cement plugs to fail frequently. Setting a cement plug two, three or even four times creates massive financial problems and causes unnecessary delays in drilling schedule.

The decision tree enables the simulation of the success of the cement plug in the forefront, with the possibility of changing some of the input variables during design phase rather than switching parameters during the actual job. The developed analysis tool as it exists, is not a graphics user interface loaded simulation software. Such GUI loaded software already exists in the industry. The focus here is more a field applicable and field ready tool that can be easily operated in the oil and gas field. Nearly all of the input variables can be measured or tested in small labs on the drilling rig without much costs and effort.

Before the structure and the individual components of the data tool can be defined, a detailed literature review and failure analysis was executed (Chapter 2 and Chapter 4). To do so, more than 30 different papers as well as industry related books and literature are examined and assessed. Most of the papers cover individual cement plug issues and challenges and also provide the appropriate case history. In a next step, a circumstantial root cause analysis is done (4.2), to rate and evaluate the problems. The root cause analysis proves and demonstrates that the vast majority of cement plugs fail because of contamination. Contamination either because the plug base or base fluid breaks down and the cement slumps through or because of swabbing induced contamination during pulling out of hole after the plug was balanced. Another frequently observed problem is the reduced strength property of the cement. If the applied compressive strength of the kick-off plug is smaller than the strength of the formation where the sidetrack is planned, a kick-off is nearly impossible since the drill bit is not guided into the desired location but drills out the cement plug in the existing hole. Beside contamination and strength issues it was assessed that insufficient bonding between the cement plug and the borehole wall contribute to unsuccessful plug jobs. Industry partners confirm the outcome of the root cause analysis and report, that issues become even worse in deviated wellbores. As a consequence of the results of the root cause analysis, it is decided to subdivide the software into the following four modules:

- Slurry Volume Design
- Plug Base Design
- Mud Removal Design
- Pull Rate Design

The individual parts are also designed as decision tree modules and provide the various steps and different options that are necessary, to achieve the best available design parameter for the planned kick-off plug.
The advantage of a module-based structure is the quick change or improvement of individual parameters or options if one decides to make improvements on the decision tree. Figure 29 shows the main page of the design program called “Quantum”, with the already described four modules. By clicking on the start button beside each module, the program will switch to the selected design step and one can follow the instructions on the page.



Comments:
- The "Quantum" data analysis tool is developed to assess the design parameters for a kick-off plug.
- The data tool is subdivided into four different modules (slurry volume-, plug base-, mud removal- and pull rate design).
- Follow the decision tree matrix by klicking on the "START" button beside each individual module. If one module is finished and delivers a practical design parameter, the appropriate boxes will change their colours.
- Use the "UNIT CONVERTER TOOL" to convert input variables between SI and oilfield units, if needed; The converter tool will be provided on each module page.
- The "RESULT" button delivers a summary report of all input- and design parameters which can be printed.

Figure 29: Main page of analysis tool
The main page of the design software contains the four different modules of the tool. By clicking on the start button beside each module, one will get to the individual subsections of the tree. Beside the different modules, also a unit converter application and a result button are implemented. If one of the modules is complete, a box with a green background and an information message pops up in order to indicate that the specific design parameter is assessed. The software is called QUANTUM, since four different design parameters are used to predict the outcome of the cement job.

If one has finished a module, the individual boxes will change the colour form light grey to green to implement that this module is already processed (Figure 30). If all modules deliver an applicable output, all branches appear in a green colour and one can edit the result.

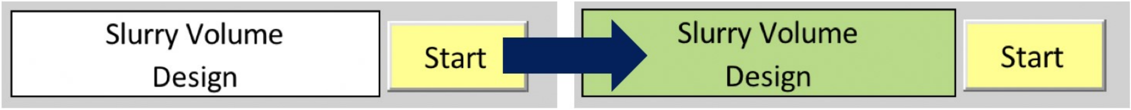


Figure 30: Colour change of module box
If individual design step is processed the colour of the box will change at the main page, indicating that an applicable output parameter is delivered.

Beside the decision tree features, a unit converter application is invented and added to every module. The unit converter is symbolized by three gear wheels and a "unit converter" button (Figure 31). Depending on the working location, the oil and gas industry uses either SI units (metric units) or oilfield units for their calculations. Although one can select in nearly every module between SI- and oilfield units, some of the raw data may be provided from the manufacturer or the laboratory in a different unit system than needed. For this reason, the unit converter can be a helpful tool to calculate between the different unit systems.

Figure 31: Unit converter symbol
By clicking on the unit converter symbol, a separate application will pop up. The engineer can use the tool do calculate e.g. density, volume or length data between the different systems.

Every module delivers field applicable output parameters for the given challenges discussed above. The individual design parameters are calculated with different mathematical formulas derived from several papers and technical literature. The mathematical formulas are assessed and verified with additional laboratory tests conducted by the individual authors respectively. The output parameters of the decision tree which is invented in this master thesis, is also verified by several laboratory simulations and experiments. The distinct lab tests and their results are discussed in Chapter 6 in more detail. Chapter 6.3. includes experimental research on a novel compressive strength enhancing material. The subsequent tests as well as the output and suggestions are described in more detail in the mentioned passage.

In the following sections, all the particular decision tree modules, their application, technical details, options and mathematical background are exemplified in more detail.

5.2 Different Modules

The data analysis tool is grouped into four different modules. Each module covers one of the major challenges, benchmarked via root cause analysis, that lead cement plugs to fail on a regular basis. Below, all four branches are discussed in detail. It should be noted, that the mathematical formulas used within a module respectively, require either all SI or oilfield units as input variables. A mixture of SI and oilfield formulas within one module was avoided. As a consequence, input variables are converted within the formula or left as they are, depending on the unit system in which the formulas are derived.

5.2.1 Module 1- Slurry Volume Design

Research has shown, that one contributor to an unsuccessful cement plug is the wrong assessment of the slurry volume that is needed for the plug job. Several papers (e.g. J. Heathman and Carpenter 1994) reported, that especially in OH sections, only an average borehole diameter was assumed rather than running a caliper log. These unprecise volume calculations often result in a too small cement plug length, with the consequence of insufficient additional sacrificial slurry on top of the plug, leading to massive contamination of the upper section of the actual good cement. When one tries to kick-off at the desired location, the bit will not be guided into the designated direction because of the contaminated fraction in the upper part of the plug. Either no sidetrack is possible or the kick-off happens way deeper than expected, where the plug provides its desired compressive strength. Papers recommend running a caliper log and add an adequate excess volume (to act as a contamination buffer) to the calculated yield. If the top of the sidetrack plug is tagged too high, one can dress the plug off, while the slurry is still in his green stage (J. Heathman and Carpenter 1994).

For the slurry volume calculation in the module, one can select fist between SI and oilfield units and subsequently between a CH or OH design (depending where the sidetrack is planned in reality). If one has to design a kick-off in an OH section of the borehole, the module of the tree demands the caliper log measured average diameter of the wellbore. Furthermore, it is in one’s liberty to decide if an additional safety for hole uncertainties should be added to the calculation or not. A pop-up reference recommends adding 10% or less. Another important fact, that is often not considered in any cement volume calculation are the exact IDs and ODs of the casing. Neglecting this fact, pipe steel volumes are not included in any volume calculation, consequently falsifying the slurry estimation. To implement the steel volumes, the program also provides the possibility of calculating the exact IDs by taking the wall thickness of the pipes into consideration. If one decides to use the average diameters, the wall thickness input variable can be neglected. The program was developed for a balanced cement plug job. In case that the plug is set via a stinger, a DP or a combination of both, a pop-up note recommends using a single size pipe either through the whole length of the wellbore or at least across the complete length of the planned plug plus some safety. The consequence of a combination of different DP diameters within the plug length are massive swabbing induced currents and disturbance when the pipes are pulled out of hole after balancing the plug. In such cases, a contamination prediction becomes nearly impossible, even for sophisticated simulation software. If possible, a single size cementing pipe should be used through the whole interval of the wellbore.

For the calculation of the slurry volume needed for the balanced cement plug job, following equations are used (all formulas in the slurry volume module are oilfield unit formulas, therefore SI input variables are converted within the formula respectively. Here, only the oilfield unit formulas are presented):

[1] Casing ID [in]

[2] Annular capacity between drill pipe or stinger and hole/ casing [ft³/ft]

[3] Stinger or DP capacity [ft³/ft]

[4] Number of sacks of cement required for given plug length [Number of sacks]

$$Casing\ ID = Casing\ OD - Wall\ thickness\ of\ casing \qquad [1]$$

$$\frac{{D_{Hole}}^2\ or\ {ID_{Casing}}^2 -\ {OD_{Drill\ Pipe/Stinger}}^2}{183.35} \qquad [2]$$

$$\frac{{ID_{Drill\ Pipe\ or\ Stinger}}^2}{183.35} \qquad [3]$$

$$Number\ of\ sacks = \frac{Plug\ lenght\ [ft] * ([2] + [3]) * Excess\ [\%]}{Slurry\ yield\ per\ sack\ [ft^3/sack]} \qquad [4]$$

Using the above described equations [1]-[3], the number of sacks of cement needed to execute the plug job is calculated at the end [4]. The program rounds the sack number automatically up to the next higher value. This number will also automatically be transferred into the plug report of the program. For calculating the number of sacks required, following input parameter must be available:

- Casing OD/ or caliper measured OH diameter [in or mm]
- Casing wall thickness [in or mm] (optional)
- Drill pipe or stinger OD [in or mm]
- Drill pipe or stinger ID [in or mm]
- Length of planned kick-off plug [ft or m]
- Slurry yield per sack of cement [ft³/sack or m³/sack]

Additionally, a safety for hole uncertainties [%] (in OH design) and cement excess volumes [%] can be added if required. Figure 32 represents a schematic drawing of the slurry volume design module.

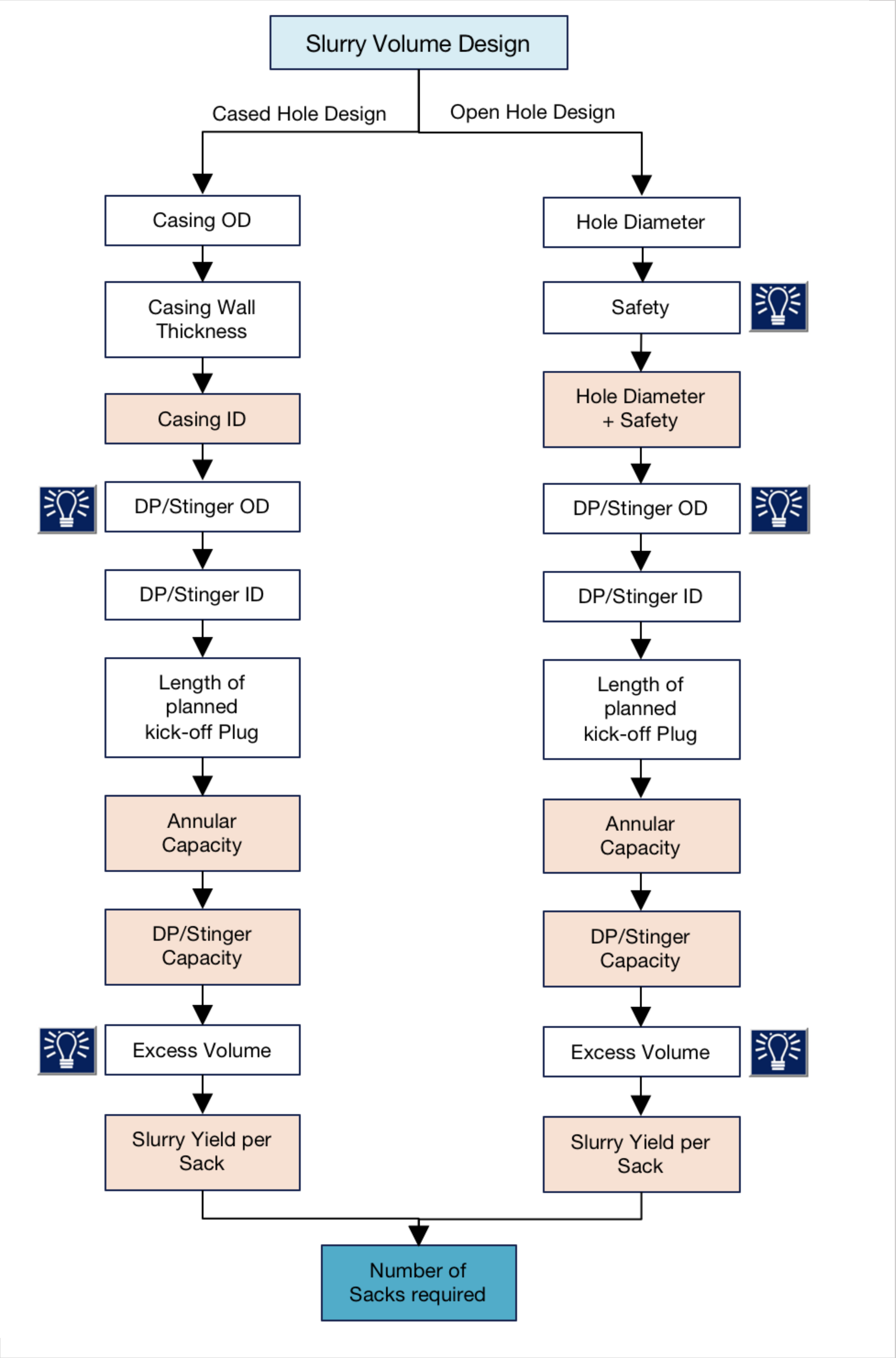


Figure 32: Schematic illustration of module 1 (slurry volume design)
The figure shows the schematic structure of the slurry volume design module of the decision tree. The white boxes require input variables, whereas the brown ones deliver intermediate results. The light bulb symbol indicates a pop-up window that provides useful information for the user.

5.2.2 Module 2- Plug Base Design

A competent plug base is a key requirement for a successful cement plug. During a conventional cement plug operation, the plug itself is normally placed off bottom and not on a stable matrix such as a rock. The plug has to be installed somewhere along the wellbore trajectory, where either governmental regulations demand it (e.g. P&A) or where subsequent operational procedure require it (kick-off or LC plug). If the plug is placed across an incompetent base, physical peculiarities such as extrusion effects (4.1.3.2) or the Boycott effect (4.1.3.3) can lead to slumping phenomenon where the cement flows down the wellbore, pushing at the same time the lighter base fluid into the undamaged cement matrix. As a consequence, either a massive contaminated or an instable and soft cement plug is the result. Because of the importance of the correct selection of the plug base to the success of a cement plug job, it is decided to assign the second module to this issue.

Figure 33 shows the principal structure of the second module. Before the right plug base can be assessed with the program, a selection between a cased hole or an open hole placement has to be done. If a sidetrack is performed from a cased hole section of the wellbore, the first option for a plug base should always be a mechanical bride plug rather than a viscous one. Literature review has proved that mechanical bride plugs, if set properly, are the best available alternative in cased sections of the wellbore (Nelson and Guillot 2006). The reasons are on the one hand a solid, mechanical device that prevents the cement from slumping through (Boycott effect and extrusion effect are disabled) and on the other hand a sealing assembly in terms of packer elastomers or metals that prohibits the exchange of fluids at the base of the zone of interest. Nevertheless, literature also reports about bridge plug limitations (Chapman et al. 2008). The sealing and anchoring efficiency can be reduced dramatically if the plug is set in and OH section (especially if the hole is out of gauge). For this reason, the program selects in case of an OH sidetrack a viscous plug base solution as the first option. Furthermore, temperature effects and corrosive environments can harm the bridge plug assembly.

If one has to design a cased hole sidetrack, the program will provide a bridge plug solution as a first option. Following the decision tree, the second limitation is the temperature. The program asks for the wellbore temperature at the point where the plug base should be installed. Chapman et al. (2008) reports from problems of sealing efficiency if elastomers are applied at temperatures above 150°C (300°F). If the bottom hole temperature at the zone of interest exceeds the above-mentioned threshold value, the decision tree suggests the selection of metal to metal bride plugs rather than metal to elastomer bridge plugs. A further limitation is a corrosive environment. Chemical induced degradation of elastomers and non-corrosive protected metals can lead to a collapse of the bridge plug. Therefore, in case that a corrosive environment is expected, the option for metal to metal plugs assembled with CRAs (corrosive resistant alloys) will be provided. The last option that has to be selected in this branch is the availability and delivery time. If the elected bridge plug type is in stock, the plug base design is finished, and one can focus on the next module. In case that the selected item is either out of stock or faces a delivery time of several weeks, the allocated solution has to be rejected.

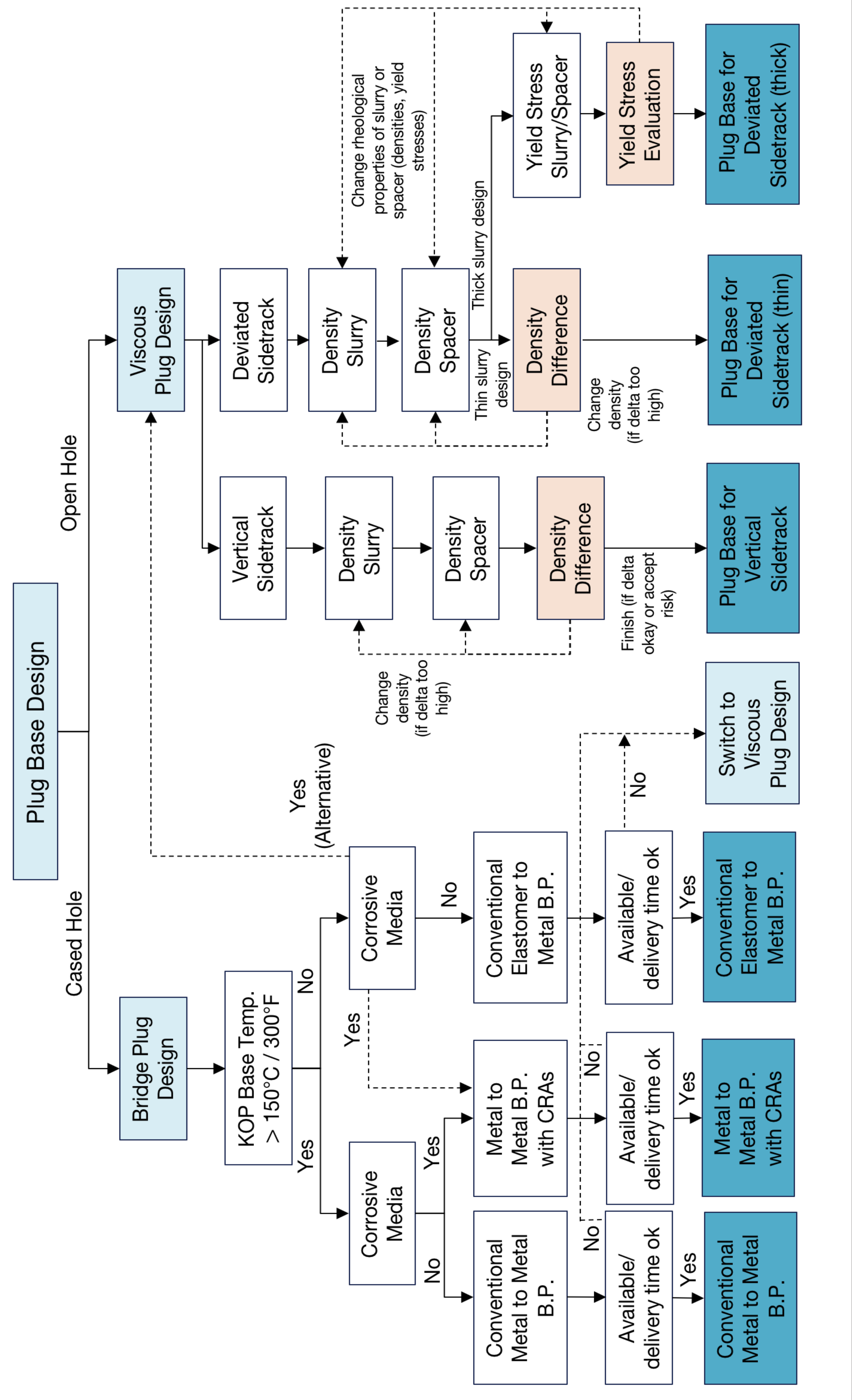


Figure 33: Schematic illustration of module 2 (plug base design)

For such circumstances one will be provided with the alternative viscous plug design option. This option follows then the same steps and suggestions like in an open hole plug base design case.

Designing a cement plug base for an open hole sidetrack, requires different input parameters. Literature recommends a viscous base fluid rather than a mechanical solution, since hole irregularities or lithology specifics can lead to massive problems when setting the mechanical tool at the designated location, facing at the same time the above described issues (Broussard, Templeton, and Travis 2009; Chapman et al. 2008). A viscous base fluid is easier to handle, excuses weak or instable wellbore conditions and can be placed with the same drillstring, that is also used for placing the cement. However, a major disadvantage is the dynamic behaviour of the different fluids. In contrast to the mechanical plug base, a viscous base fluid can move and commingle with the cement slurry. If the density of the base fluid is not selected carefully, gravity driven forces cause the cement slurry to fall through the plug base, resulting in an instable, contaminated or even useless kick-off plug (Beirute 1978). For this reason, the open hole branch of the design tool provides a selection option between a vertical or deviated sidetrack location. R. C. Smith (1984) and J.F. Heathman (1996) performed several experiments on slurry and base fluid behaviour in vertical parts of a wellbore. If the density difference exceeds a certain threshold, the cement starts to wind in a helical shape down the borehole, pushing at the same time lighter base fluid in the upper parts of the plug. On the other hand, a cement plug that is set in a deviated section of the wellbore suffers from the Boycott- and extrusion effect. Calvert, Heathman, and Griffith (1995) stated that thin slurries are influenced by the Boycott effect, whereas Crawshaw and Frigaard (1999) developed a mathematical model that describes the extrusion and interface stability between thick cement slurries and the plug base fluid.

If an open hole sidetrack is required, the decision tree program takes the above described phenomena into account. For a vertical plug location or a deviated one with a thin cement slurry composition, the density difference between the base fluid and the cement is the major controlling factor. For the evaluation, the simple equation [5] is used by the program. If the input parameters exceed the appropriate threshold value, an error message shows up. The engineer is asked to change the densities of the slurry or the base fluid, until the delta undercuts the pre-defined threshold.

$$\Delta_{Density} = \rho_{Cement\ Slurry} - \rho_{Plug\ Base\ Fluid} \tag{5}$$

The input variables for equation [5] are either [kg/m^3] if the SI unit system is used or [lbm/gal] if one uses oilfield variables. The program automatically identifies the unit system and selects the right laboratory defined threshold value.

In case of a thick or dense slurry as an input variable, the program picks a different design option. Here, the stability of the interface as well as the density difference between the base fluid and the cement is important. For the stability evaluation, the yield stresses of the cement [6] and the base fluid [7] must be calculated. The mathematical principle was derived by Crawshaw and Frigaard (1999) and delivers a theoretical dimensionless yield stress value for the cement and the base fluid respectively. Crawshaw and Frigaard, performed experiments and identified the stability limits for a 10° and 45° wellbore inclination (Figure 21). The stability limit plot is also assembled for the distinctive module (Figure 34). It is decided to plot only the 45° limit since this value provides the worst-case scenario in terms of inclination and instability. If the calculated dimensionless yield stresses intersect within the green area, the selected input values may provide a stable interface, whereas an intersection in the red area may cause instable plug base conditions. In this case, the engineer is asked to change either the densities or the rheological parameters of the cement or the base fluid respectively until the stress evaluation provides a stable interface behaviour.

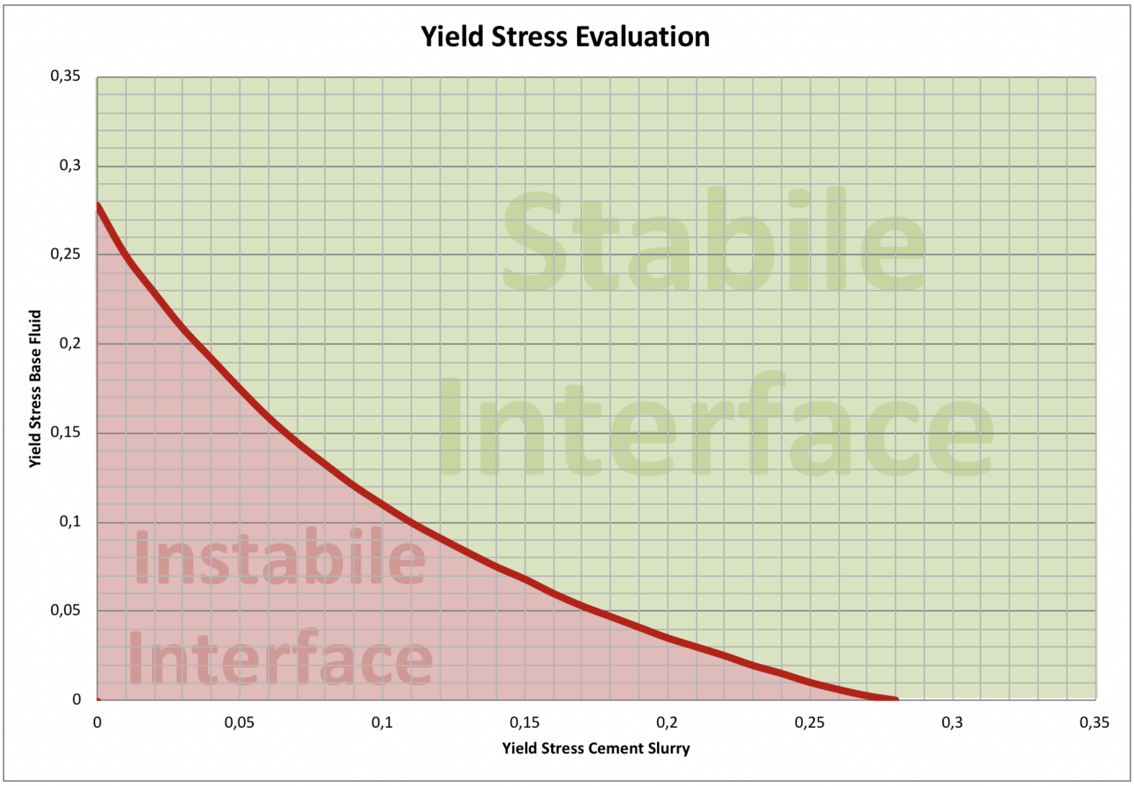


Figure 34: Yield stress evaluation plot

The figure shows the modified plot for the yield stress evaluation. The plot is assembled for the module of the software, indicating if the input variables deliver a stable or an instable interface. The red line represents the 45° stability limit, assessed by Crawshaw and Frigaard in 1999. If the intersection of the calculated yield stress of the cement and the plug base fluid is within the green area, a stable interface is expected and one has finished this module. If the intersection is within the red area, or at the 45° limitation curve, one is asked to change the input variables. Since the hole diameter (which is one input variable) is fixed, either the densities of the fluids or the rheological parameters (yield stresses) must be changed, until the plot delivers a stable interface forecast.

For the evaluation of the dimensionless yield stresses, the data analysis program uses following equations:

$$\tau_{y,cement} = \frac{\hat{\tau}_{y,cement}}{\Delta\rho * g * D_{Hole/Casing}} \qquad [6]$$

$$\tau_{y,Base\ Fluid} = \frac{\hat{\tau}_{y,Base\ Fluid}}{\Delta\rho * g * D_{Hole/Casing}} \qquad [7]$$

Equation [6] calculates the predicted yield stress of the cement and equation [7] the predicted yield stress of the base fluid. Both values are used to forecast the stability of the interface in Figure 34. The base fluid yield stress is plotted on the y-axis, and the slurry yield stress on the x-axis. Using the formulas [6] and [7], following variables are used:

- $\hat{\tau}_{y,Cement}$ → Measured yield stress of the cement [Pa or lbf/100ft^2]
- $\hat{\tau}_{y,Base\ Fluid}$ → Measured yield stress of the base fluid [Pa or lbf/100ft^2]
- $\Delta\rho$ → Cement and base fluid density [kg/m^3 or lbm/gal]
- D → Diameter of the hole or the casing [mm or in]
- g → Gravity (already provided by the program)

5.2.3 Module 3- Mud Removal Design

The third module of the analysis program covers mud removal problems. Mud removal issues cause a lot of troubles during drilling operations, not only when a casing is cemented in place, but literature review has shown that kick-off plugs also fail if the bonding between the casing or the borehole wall and the cement plug is not sufficient. If the removal of partly dehydrated-gelled drilling mud and the filter cake is insufficient, an unacceptable and poor cement job will be the result- nevertheless if it is a primary or secondary cement operation (K. M. Ravi, Beirute, and Covington 1992). The bad bonding is caused by mud and filter cake residues that adhere either at the casing or the formation. If the washer (spacer) properties cannot meet the required specifics to break the strength of the gelled drilling fluids, a contaminated and poorly bonded cement plug will be the consequence. James F. Heathman et al. (1994) reports from events, where operators tried to kick-off with a perfect cement plug but failed at the end because the plug began to rotate when the drill bit exerted torsional force on the structure. Because of such case studies and the fact that the issue is often underrated or neglected, a third "mud removal" module is introduced to the decision tree program. This module supports the engineer in designing a spacer that fulfils the requirements to remove or erode the gelled drilling mud and the mud cake from the wellbore. Figure 35 shows the classification and structure of the module.

A useful concept of drilling mud removal was introduced by K. M. Ravi, Beirute, and Covington (1992). They introduced the term "erodability" and delivered mathematical equations to assess the minimal pressure drop required to remove the gelled drilling fluid from the wellbore successfully. The concept is resumed for the decision tree and constitutes the foundation for the third module. A spacer, designed with the above described concept, delivers a wall shear force that is greater than the yield stress of the filter cake or the drilling mud. If this principle is fulfilled, drilling fluids and its residue should be eroded successfully from the borehole. The erodability of the drilling liquid can be assessed with a mathematical equation [8]. When the erodability of this fluid is known, one can derive the shear stress [9] and hence the pressure drop [10] that is required at the wall to remove the mud (K. M. Ravi, Beirute, and Covington 1992). Another big advantage about this concept is the possibility of designing the rheological parameters of the spacer as well as minimum pump flow rate in one step without the requirement of additional effort and input variables.

The problem of assessing the right parameters is more sophisticated than expected, since friction induced forces along the wellbore can influence the outcome of the calculations severely. To include the friction and its impact on the fluid specifics, a further concept has to be introduced to the design module. Shah and Sutton (1990) developed a mathematical relationship to predict the friction pressure during pumping operation. They used a Bingham-plastic model as a foundation for their research. Here, the shear stress τ is related to the shear rate γ by the yield stress τ_0 and the plastic viscosity μ_p. The shear stress and the sear rate are two constants that need to be assessed by lab measurements in the forefront. Nguyen (1996) stated that spacers, drilling muds and cement slurries can be characterized either by Bingham-plastic or power law models.

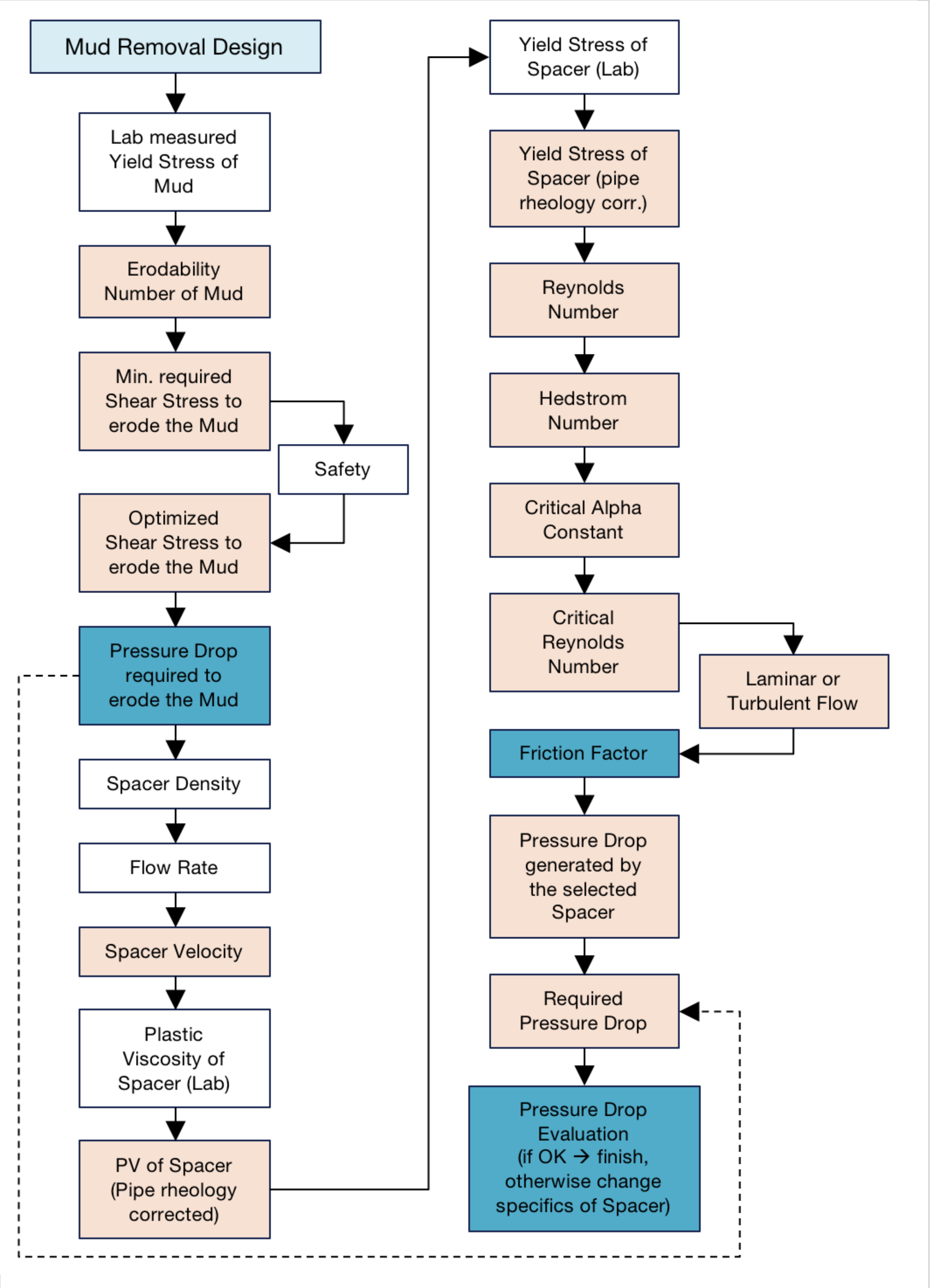


Figure 35: Schematic illustration of module 3 (mud removal design)

The figure shows the structure of the third module of the decision tree program. The white boxes require input variables, whereas the brown ones deliver intermediate results. The module is subdivided into three parts. In the first part the pressure drop, needed to erode the drilling fluid is calculated. In the second part, the friction coefficient is assessed and in the third part a pressure drop evaluation is done. If the pressure drop, exerted by the spacer is smaller than the required one, spacer properties or the flow rate must be changed.

For the calculation of the friction factor in the module, it is decided to use the experimentally proved concept that was developed by Shah and Sutton (1990). Because of the statement of Nguyen (1996) a Bingham-plastic rheological model can be accepted as a base to assess the washer specifics for the cement plug job. In the following, all necessary design steps and underlying equations will be discussed in more detail.

It has to be mentioned that also in this design module, one can select between the SI and oilfield unit system for the input variables. The program will automatically convert the input variables for the appropriate equations if needed. As a first step, the yield stress of the drilling mud τ_m that has to be eroded from the borehole wall must be measured in the laboratory. This yield stress value provides the base for all further calculations. The input variable can be either measured in Pa or lbf/100 ft^2, depending on the unit system that was chosen at the beginning. With this value, the erodability of the mud [8] can be assessed. This number provides the input for the calculation of the minimum wall shear stress τ_{wall} that is required to erode the drilling mud [9]. The design program features an "safety" option, where one can add a safety in % to increase the shear value needed to remove the gelled fluid and mud cake. The safety value is automatically pre-set to 30% but can be changed to any % by the engineer. The safety delivers a so called "optimized" shear stress value to erode the mud and results in higher design output parameters for the washer, even if the mud would be detached at lower values. With the optimized shear stress, the pressure drop $\Delta p_{req.}$ needed to erode the drilling mud can be calculated [10]. (Note: all equations are given in oilfield unit system).

$$Erodability = \frac{600}{\tau_m} \tag{8}$$

$$\tau_{wall} = \frac{600}{E} \tag{9}$$

$$\Delta p_{req.} = \frac{4 * (l * 12) * (\frac{\tau_{wall}}{100 * 144})}{ID_{H/C} - OD_{DP/S}} \tag{10}$$

For the formulas [8] – [10], following variables are used:

- τ_m → Lab measured yield stress of drilling mud [Pa or lbf/100ft^2]
- E → Erodability [-]
- l → Length of interval (e.g. cement plug length) [m or ft]
- τ_{wall} → Wall shear stress [Pa or lbf/100ft^2]
- $ID_{H/C}$ → ID of hole or casing [mm or in]
- $OD_{DP/S}$ → OD of drill pipe or stinger [mm or in]

Equation [10] delivers the minimum pressure drop required to erode the drilling fluid from the borehole wall. Based on this value, the spacer properties are designed in the next steps. To do so, the above described friction pressure loss must be considered, in order to get useful parameters for the washer. The base for all further calculations is the concept developed by Shah and Sutton (1990). As needed in the future, these calculations can be substituted by another calculation procedure if that is more suitable. The input parameters are the planned spacer density ρ_{Spacer}, pump flow rate, plastic viscosity $\mu_{p,Fann}$ and yield stress $\tau_{0,Fann}$ of the spacer. If the designed pressure drop, calculated with the input variables and exerted by the washer, is lower than the assessed value in [10], one must change the spacer properties.

To calculate the theoretical pressure drop of the spacer Δp, a friction coefficient f must be identified. In a first step, the rotational- viscometer derived plastic viscosity $\mu_{p,Fann}$ and yield stress $\tau_{0,Fann}$ of the spacer have to be corrected. With this correlation, the lab measured values are adapted to a pipe rheological flow of the fluid. Equations [11] and [12] represent the correction for the plastic viscosity and yield stress respectively. If these steps are accomplished, the program automatically calculates the spacer velocity [13], Bingham-plastic Reynolds number N_{Rep} [14], the Hedstrom number N_{He} [15] and the Critical Reynolds number $N_{Rep,critical}$ [16] of the system. It should be noted, that the Critical Reynolds number is used to describe the transition between a laminar or turbulent flow regime of a fluid. If the evaluated Reynolds number is smaller than the Critical Reynolds number, a laminar flow regime is present, whereas a Reynolds number higher than the critical one will indicate a turbulent fluid flow. The program automatically determines the ratio and gives back the prevailing flow regime. The assessment of the Critical Reynolds number is based on the Hanks theory (Hanks 1963), but was modified by Shah and Sutton (1990), based on their experimental findings. For the evaluation of the Critical Reynolds number, a critical alpha constant α_c [17] must be assessed in the forefront. The equation for the critical alpha constant was also modified, because experimental values and Hanks theory-based numbers differed from each other. According to Shah and Sutton (1990), the above described correlations are valid for Hedstrom numbers between $1*10^1$ to $1*10^6$. When all values are calculated, the friction factor [18]/[19] can be identified, depending if the flow regime is laminar or turbulent. In case that a laminar flow occurs, equation [18] is used by the program and if it turns out that the flow is turbulent, equation [19] becomes valid. In case that [19] is used, two Hedstrom number dependent constants A and B are selected automatically by the design module. The friction factor is finally used as an input parameter for the evaluation of the spacer delivered pressure drop [20].

$$\mu_{p,Pipe} = e^{0.9815*\ln(\mu_{p,Fann})-0.03832} \quad [11]$$

$$\tau_{0,Pipe} = 1.591 * \tau_{0,Fann} - 2.149 \quad [12]$$

$$v_{Spacer} = 17.16 * \frac{Flow\ Rate}{{ID_{H/C}}^2 - {OD_{DP/S}}^2} \quad [13]$$

$$N_{Rep} = \frac{927.6 * v_{Spacer} * \left(ID_{H/C} - OD_{DP/S}\right) * \rho_{Spacer}}{\mu_{p,Pipe}} \quad [14]$$

[15]

Different Modules

$$N_{He} = 37010 * \frac{\tau_{0,Pipe} * \left(ID_{H/C} - OD_{DP/S}\right)^2 * \rho_{Spacer}}{{\mu_{p,Pipe}}^2}$$

$$N_{Rep,critical} = \frac{N_{He} * (0.968774 - 1.021829 * \alpha_c + 0.050651 * {\alpha_c}^4)}{8 * \alpha_c} \qquad [16]$$

$$\frac{N_{He}}{24500} = \frac{\alpha_c}{(1-\alpha_c)^2} \qquad [17]$$

$$f_{Laminar} = 16 * \left[\frac{1}{N_{Rep}} + \frac{1}{7.9} * \frac{N_{He}}{\left(N_{Rep}\right)^2}\right] \qquad [18]$$

$$f_{Turbulent} = A * \left(N_{Rep}\right)^{-B} \qquad [19]$$

$$\begin{gathered} For\ N_{He} \leq 1.0 * 10^5 \\ A = 0.20656\ and\ B = 0.3780 \end{gathered}$$

$$\begin{gathered} For\ 1.0 * 10^5 < N_{He} \leq 2.1 * 10^5 \\ A = 0.26365\ and\ B = 0.38931 \end{gathered}$$

$$\begin{gathered} For\ N_{He} > 2.1 * 10^5 \\ A = 0.20521\ and\ B = 0.35579 \end{gathered}$$

$$\Delta p = \frac{f * l * \rho_{Spacer} * {v_{Spacer}}^2}{25.83 * \left(ID_{H/C} - OD_{DP/S}\right)} \qquad [20]$$

For the equations [11]-[20] following variables are used:

- $\mu_{p,Fann}$ → Lab measured plastic viscosity [mPa*s or cP]
- $\tau_{0,Fann}$ → Lab measured yield stress [Pa or lbf/100ft²]
- $Flow\ Rate$ → Pump flow rate [m³/min or bbl/min]
- $ID_{H/C}$ → ID of hole or casing [mm or in]
- $OD_{DP/S}$ → OD of drill pipe or stinger [mm or in]
- ρ_{Spacer} → Density of spacer [kg/m³ or lbm/gal]
- N_{Rep} → Reynolds Number [-]
- N_{He} → Hedstrom Number [-]
- $N_{Rep,critical}$ → Critical Reynolds Number [-]
- α_c → Critical Alpha value [-]
- f → Friction factor [-]
- Δp → Pressure drop generated by spacer [Pa/bar or psi]

At the end of the calculation process, the washer exerted pressure drop will be delivered as an output variable. The program automatically compares the assessed value from [10] (which is the required pressure drop for the measured drilling mud properties) with the evaluated value from [20] (the spacer pressure drop, including the friction pressure losses).

If the generated pressure drop of the spacer is smaller than the calculated pressure drop in [10], a warning message will pop up. The engineer is asked to change the input values for the spacer. Since casing or hole diameters, as well as drill pipe or stinger diameters are fixed, one can only change the spacer density ρ_{Spacer}, the flowrate at the pump, the plastic viscosity $\mu_{p,Fann}$ or the yield stress $\tau_{0,Fann}$ of the spacer fluid. By adjusting these values, an appropriate pressure drop should be maintained. The final values will be transferred into the design report of the program. The big advantage of this module is, that not only the mud removal can be designed but also the spacer specifics and the required flow rate, without including additional design steps.

5.2.4 Module 4- Pull Rate Design

Calculating the right slurry volume, designing the right plug base fluid specifics and achieving a perfect mud removal is no warrant for a successful cement plug. If the pull rate is miscalculated, a perfect set kick-off plug can fail severely because of massive contamination of the upper part of the slurry. Marriott et al. (2006) reports that swabbing induced forces cause intermixing of the slurry and the mud when the drillpipe is pulled from the hole. J. Heathman and Carpenter (1994) showed that this phenomenon is more severe in thick slurries rather than in thin ones since dragging forces have a higher influence on viscous fluids.

The mud/cement mixture settles down forming fluid pockets in the plug matrix. When an operator tires to drill the formation, the soft and wet structure of the kick-off base cannot provide enough compressive strength. As a consequence, the plug will be drilled rather than the formation and the cementing job has to be repeated. There are many industry related examples that show the massive influence of the pulling speed on the plug integrity. Even the root cause analysis conducted in this thesis (4.2) states that more than 46% of all plug failures arise from slurry contamination (including plug base failures) resulting in a reduced compressive strength of the cement. One can see that the right selection of the tripping speed- especially when the drillpipe is pulled from the cement slurry into the drilling mud or spacer, substantially contributes to a successful kick-off plug. The fourth element of the software calculates the critical speed for the slurry and the drilling fluid and ultimately predicts the predominant flow regime if a specific tripping speed is selected. Figure 36 shows an illustration of the fourth module of the software.

The prediction of the swab pressures as well as the flow regime calculation in this module is based on the concept of Forutan and Hashemi (2011). The fundamental fluid flow equations were implemented by Gatlin (1960) and provide the base for all further predictions executed in this chapter. One reason why the concept of Forutan and Hashemi (2011) was selected is the simplicity of input data. All required properties are already measured or evaluated when using the previous modules. This facilitates the use of this program in the field since no additional measurements or investigations have to be conducted.

Prior calculating the critical speeds and flow regimes, one must enter specific fluid properties such as plastic viscosities, yield points and densities of the cement and the drilling mud. These values are already identified and can be copied from the previous modules. The first output variable of the program is the critical speed for the cement slurry and the drilling fluid. The velocity is calculated using equation [21]. In a next step, one must enter the planned tripping speed which is used to pull out the stinger pipe from the wellbore. This is an essential part since this selected speed may trigger swab pressures that drag parts of the cement slurry in the drilling mud forming in the end fluid pockets that reduce the compressive strength property of the plug. Based on the tripping speed, the program calculates the average flow velocity in the annulus between the stinger pipe and the wellbore. To do so, equation [22] is used. After evaluating the annular velocity, the predominant flow regime is determined.

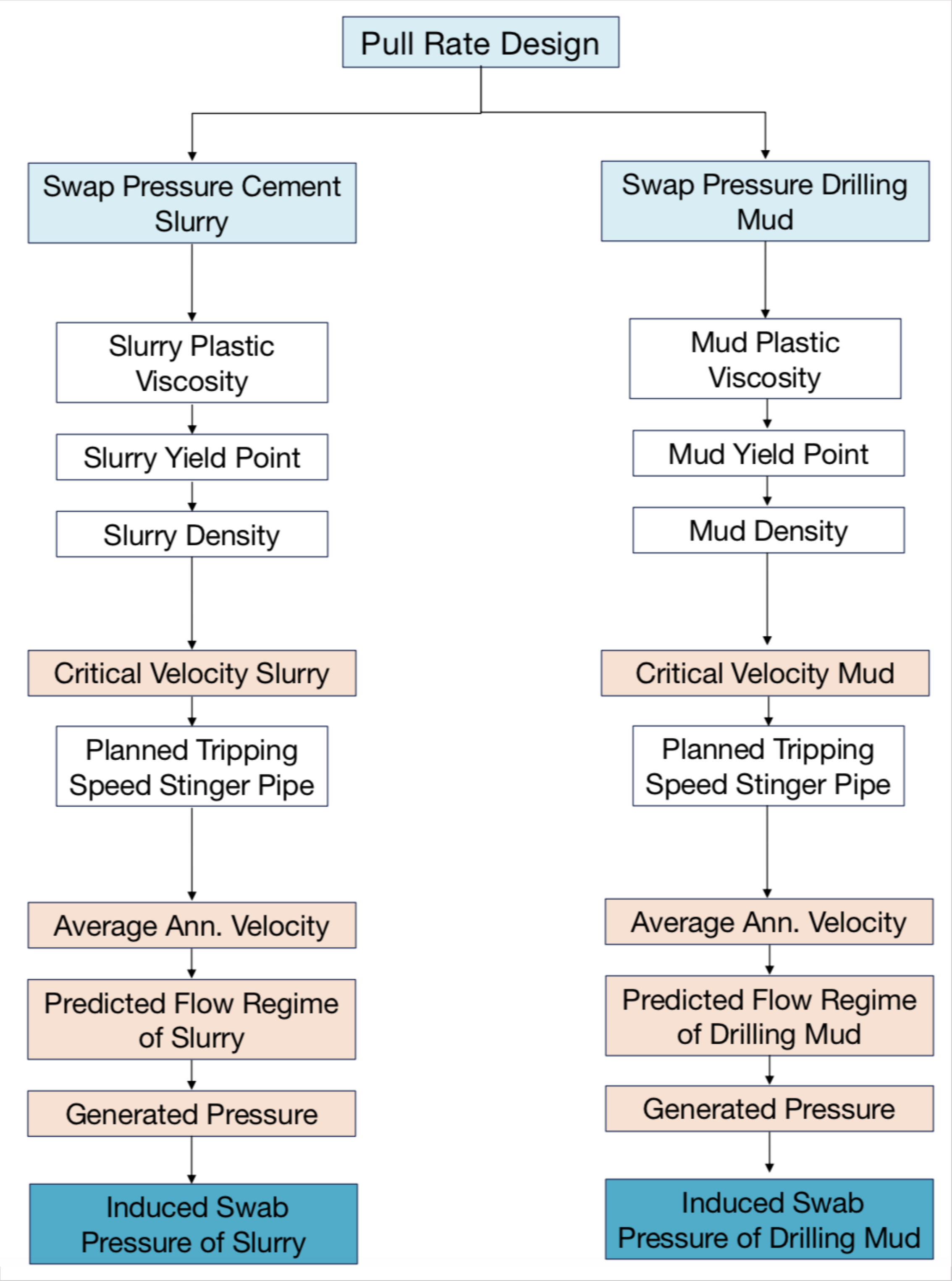


Figure 36: Schematic illustration of module 4 (pull rate design)

The picture shows the structure of the fourth module of the decision tree program. The module is subdivided into two parts. Each part returns the critical flow velocity as well as the induced swab pressures during tripping for the cement slurry and the drilling mud respectively. Exceeding the critical velocity and inducing high swab pressures can lead to massive contamination of the kick-off plug.

The program evaluates the flow regime for both, the cement slurry and the drilling mud. Based on the selected pipe running speed, the critical velocity and the calculated annular velocity, either a laminar or a turbulent flow regime is prevailing. In case that a laminar flow regime occurs, the pressure drop is calculated with equation [23]. If the selected parameters trigger a turbulent flow regime, the program uses equation [24] to calculate the pressure drop. The more complex turbulent flow requires the calculation of a Reynolds Number [25] and a friction factor [26]. Morrison (2013) developed a friction factor correlation for smooth pipes [26] that reduces to $f = 16/Re$ at low Reynolds numbers and becomes the Prandtl correlation at high Reynolds numbers. Because of the more sophisticated manner of this friction factor calculation, this developed correlation is preferred to the equation used by Forutan and Hashemi (2011). As a last step, the program evaluates the induced swabbing pressure [27] in the cement slurry and the drilling mud.

$$v_c = \frac{1.08 * \mu_p + 1.08 * \sqrt{{\mu_p}^2 + 9.3 * MW * (d_h - d)^2 * y_p}}{MW * (d_h - d)} \tag{21}$$

$$v_a = v_p * \left(\frac{1}{2} * \frac{d^2}{{d_h}^2 - d^2}\right) \tag{22}$$

$$\Delta P = \frac{L}{300 * (d_h - d)} * \left[y_p + \frac{\mu_p * v_a}{5 * (d_h - d)}\right] \tag{23}$$

$$\Delta P = \frac{f * L * MW * {v_a}^2}{25.8 * (d_h - d)} \tag{24}$$

$$Re = \frac{927.6 * MW * v_a * \ (d_h - d)}{\mu_p} \tag{25}$$

$$f = \left(\frac{0.0076 * \left(\frac{3170}{Re}\right)^{0.165}}{1 + \left(\frac{3170}{Re}\right)^{7.0}}\right) + \frac{16}{Re} \tag{26}$$

$$P_{swab} = 0.052 * MW * h * \Delta P \tag{27}$$

For the equations [21]-[27] following variables are used:

- MW → Cement/ Drilling fluid density [kg/m^3 or ppg]
- ΔP → Pressure Drop [bar or psi]
- P_{Swab} → Swab pressure [bar or psi]
- Re → Reynolds Number
- v_a → Annular flow velocity [m/sec or ft/sec]
- v_c → Critical flow velocity [m/sec or ft/sec]
- v_p → Pipe running speed [m/sec or ft/sec]
- f → Friction factor [-]
- y_p → Yield point of cement slurry or drilling mud [Pa or lb/100 ft^2]
- μ_p → Plastic viscosity of cement slurry or mud [mPa*s or cP]

5.2.5 Report

Each designed plug and the plug specifics are summarized in a report at the end of the program. The report consists of a general column where important information such as well number, sidetrack number, name of the engineer … can be inserted. Following the general part, a summary of the most important input variables is provided. The main part of the report is a schematic drawing of a general kick-off plug. The drawing includes the stinger pipe, a color code for the spacer/ drilling mud, one for the cement and one for the base fluid as well as further important numbers and parameters. The special feature of the drawing is the possibility of a schematic illustration of problematic zones. If the input variables deliver an optimized cement plug, one will get a report that indicates no critical zones (Figure 85 in the Appendix). If the input variables may cause any troubles, e.g. a high stinger pulling rate is forecasted to trigger contamination effects, the report will automatically indicate the problematic zone in the drawing (Figure 86 in the Appendix shows a cement plug where the input variables cause contamination, mud removal problems and an instable base to slurry fluid interface. The problematic zones are highlighted by a red bar and a message at the appropriate location). The report is edited in a way that it can be printed on an A4 paper as a one pager.

Chapter 6 Verification of the Tool- Laboratory Simulations & Experiments

To verify the predicted design parameters of the "Quantum" data analysis tool (Chapter 5) it is decided to assemble an experimental set-up in the laboratory. The goal is the construction of a test site using existing material in combination with particular designed new equipment that can be utilized to simulate a kick-off plug operation under downscaled field conditions. In the following chapter, the set-up as well as the execution of the experiments are discussed in more detail.

6.1 Experimental Set-Up

The idea is the construction of a model of a drilling rig with a stinger pipe assembly and a borehole under down scaled field conditions. The circumstances in the new laboratory allows the simulation of a drilling rig site with the surface installations such as a rig, pumps and pits on the top and a borehole placed on the bottom below the mast of the drilling rig. Figure 37 shows an overview of the set-up. The mini drilling rig, including all surface installations are placed on the ground floor of the laboratory, simulating the surface area of a well site. Below the rig, in the cellar of the laboratory, the borehole pipe is installed simulating a drilled wellbore in which the cement plug has to be set in order to kick off from that pre-existing borehole.

6.1.1 Upper Part- Drilling Rig & Surface Installations

Figure 37 shows the view of the complete set up, where the upper part simulates the surface installations of a drilling rig site. Figure 38 gives a more detailed overview of the upper set-up. The mini-rig (1) is a downscaled fully working model of a drilling rig, designed especially for the use in the laboratory. The rig is manufactured out of steel and has a total height of approx. 2.5 meters and a base area of 0.1m x 0.12m.

The drawworks (8) are installed in the back of the construction. To move the steel cable (3) of the rig, an AC servomotor is attached to the cable drum. The motor has a rated torque of 1.5 Nm with a maximum rotation of 4000 1/min and 325 V DC intermediate circuit rated voltage (approx. 230 VAC). The cable drum has a diameter of 90mm (3,54 in). To avoid wear and snagging tendency of the steel cables during multilayer spooling, a Lebus groove pattern is installed on the drum base. This system guides the first layer of the steel cable to fill the drum in a controlled and ordered way and allows any other multilayer to wrap precisely along the groove of the previous ones. Figure 39 shows a picture of the Lebus groove system of the drawworks drum. The drum can store approx. 25m of steel cable. The maximum hook load that the drawworks system can lift is limited to 90 kg. Under normal operating conditions, a top dive system (10) is attached to the hook of the steel cable. The top drive of the mini rig is actually a special mining motor, used to drill holes for explosive charges. To provide sufficient weight on bit (WOB), several balance weights can be mounted on the structure.

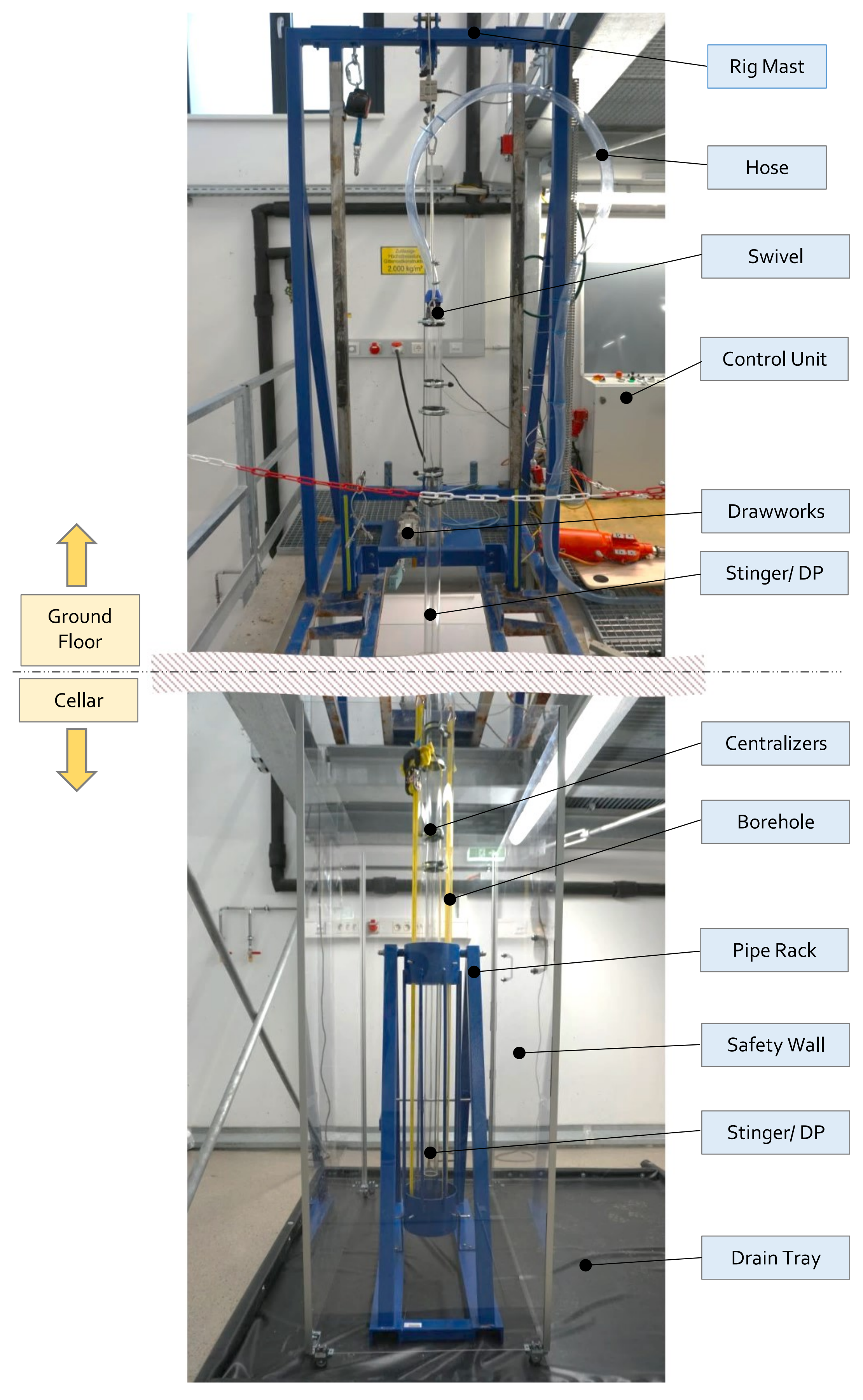


Figure 37: Complete set-up of the experiment in the laboratory

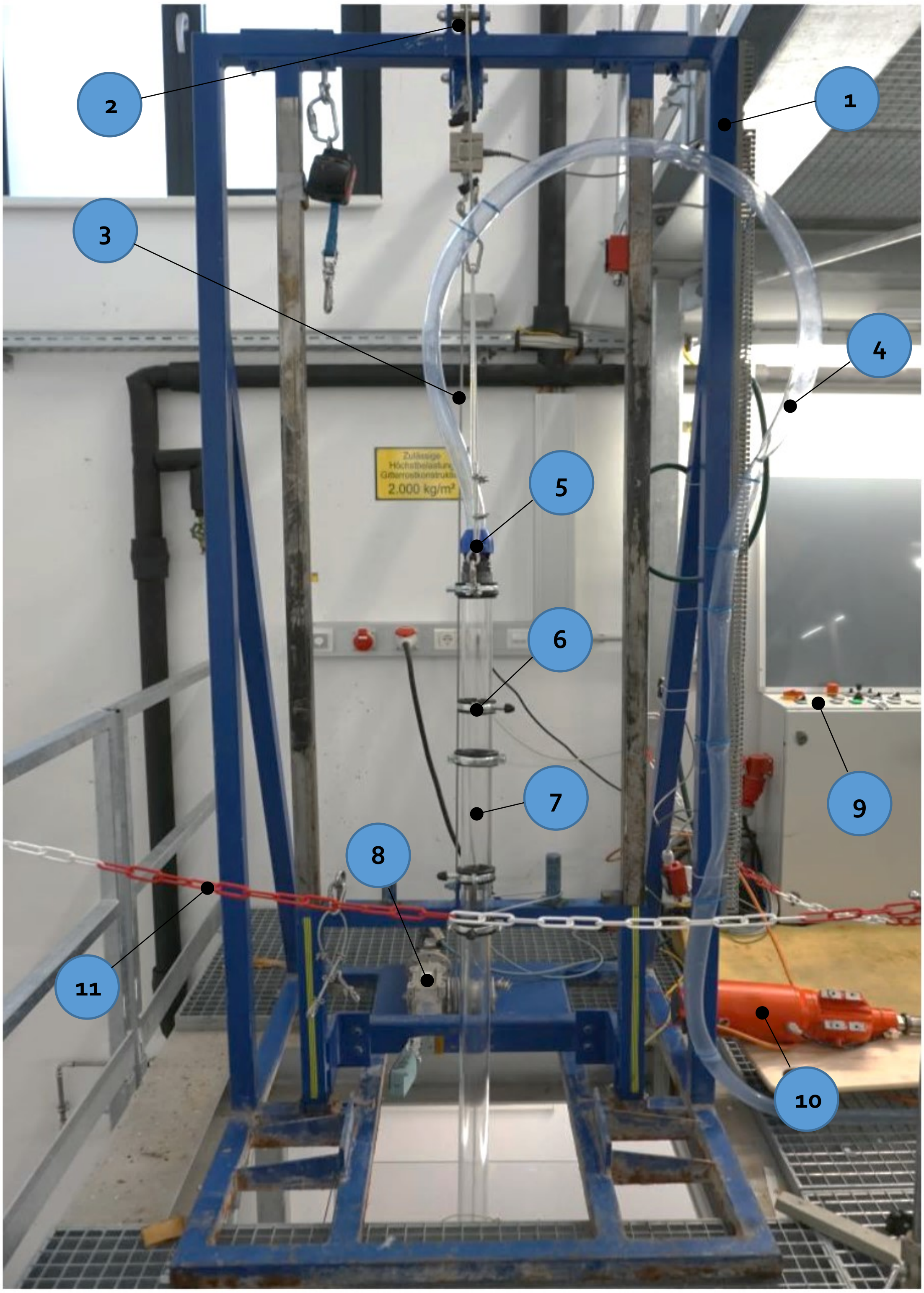


Figure 38: Upper part of the set-up (drilling rig)
The picture shows the upper part of the experimental set-up. The drilling rig (1) is located on the ground floor of the laboratory. The frame of the rig has two pulleys (2) that help to guide the steel rope (3) from the drawworks (8) to the Plexiglas drill pipe/stinger pipe (7). The fluids are pumped via the transparent hose (4) from the manifold to the borehole in the cellar. The hose itself is connected via a swivel (5) to the stinger pipe. The centralizers (6) help to keep the stinger pipe in a centred position during experimental work. The control panel (9) is used to operate the drawworks and the top drive (10) and the chain (11) marks the safety area

Figure 39: Lebus groove system of the drawworks drum

For the execution of the actual cement plug job operation, the top drive system (10) is disassembled from the rig. Instead of the drilling motor, the stinger pipe assembly (7) is attached to the hook of the steel cable. During the experiment, the different fluids (drilling fluid, plug base fluid and cement) are pumped via the transparent hose (4) and the stinger tube downhole. The swivel (5) represents the connection between the hose and the stinger (Figure 40). The swivel itself consists of a connecting nipple and a transition sleeve. The connecting nipple holds the hose securely, whereas the transition sleeve provides the crossover between the stinger Plexiglas pipe and the nipple. The easiest and safest option was to glue the transition sleeve to the Plexiglas pipe, using a special acrylic glass glue, that hardens under UV light emission. Below the swivel, a pipe hanging assembly is installed (Figure 40). The hanging assembly provides the connection ports for the steel cable. That cable is used to connect the Plexiglas pipe with the hook of the drawworks system in order to lift or lower the pipe into the wellbore.

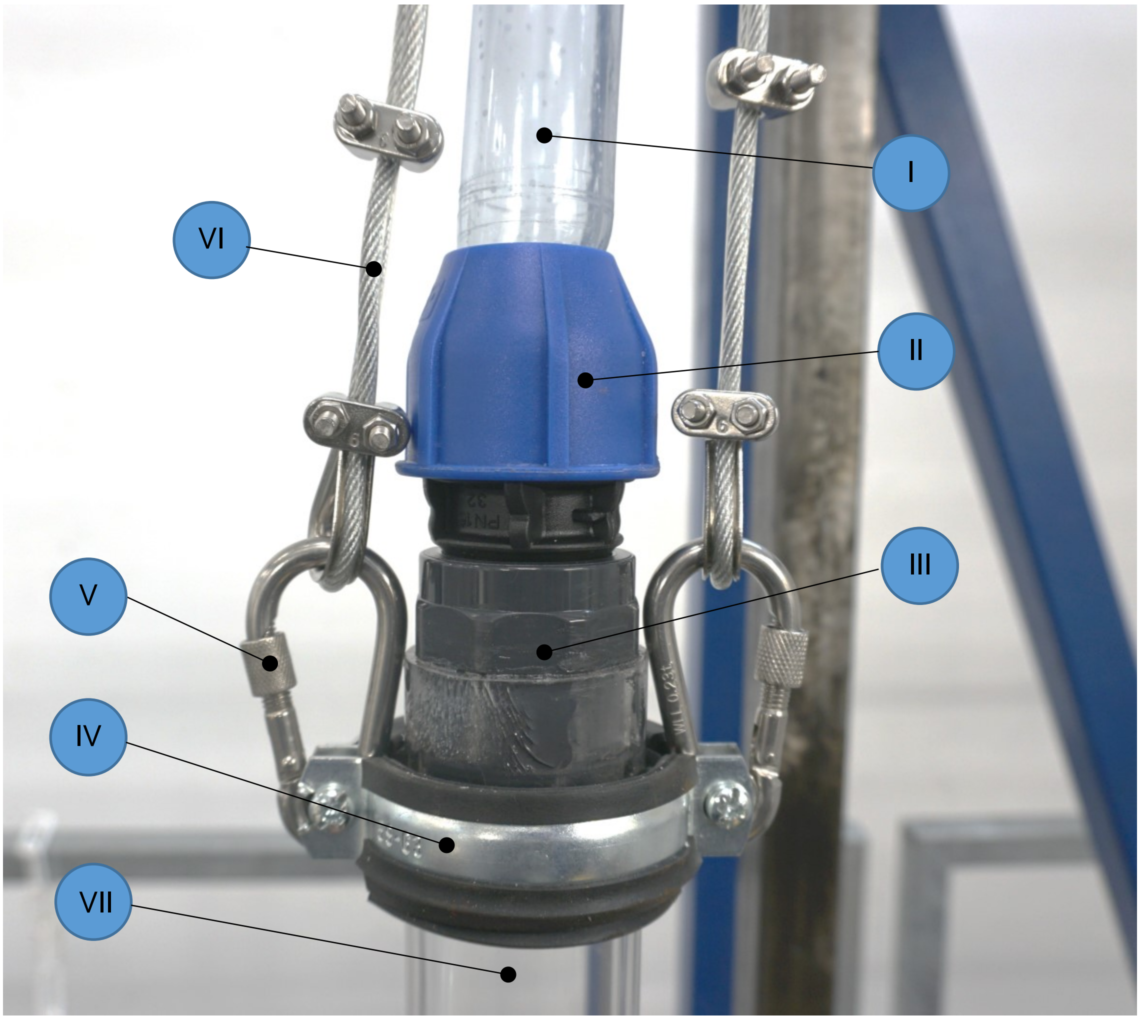


Figure 40: Swivel and hanging assembly
The hose (I) is connected via the connecting nipple (II) to the transition sleeve (III). The transition sleeve is glued to the Plexiglas stinger pipe (VII) and provides a safe crossover between the flexible hose and the stinger. Below the swivel, the pipe hanging assembly (IV) is installed. The hanging assembly includes connection ports (V), that can be used to attach the stinger steel rope (VI) with the stinger system.

To keep the drill pipe/stinger pipe (7) in a centred position, four centralizers (6) are attached to the Plexiglas pipe. The implementation of the centralizers is realized by using simple pipe clamps that are fixed to the pipe. Rubber straps on the inner face of the clamps protect the Plexiglas pipe from being scratched by the metal of the clamps and allow a strong bonding between the clamps and the pipe. A thread rod with a bold and nut and a flexible protective cap provide the distance that is necessary in order to keep the pipe centred. This combination with equal length is screwed to every of the four pipe clamps. Furthermore, every pipe clamp shows in a different direction to ensure the same distance between the drill pipe and the borehole pipe. All functions of the mini rig can be controlled and regulated from a central control unit (9). Figure 41 shows the control panel of the unit in more detail. The control unit is connected via cables to the individual components of the rig and can be turned on and off by the master switch. (VIII). The joystick (IX) is used to operate the drawworks. By pulling the joystick down, the drawworks will start to operate and lower the drillstring or top drive into the borehole. By pulling the stick up, the system will be pulled out from the wellbore.

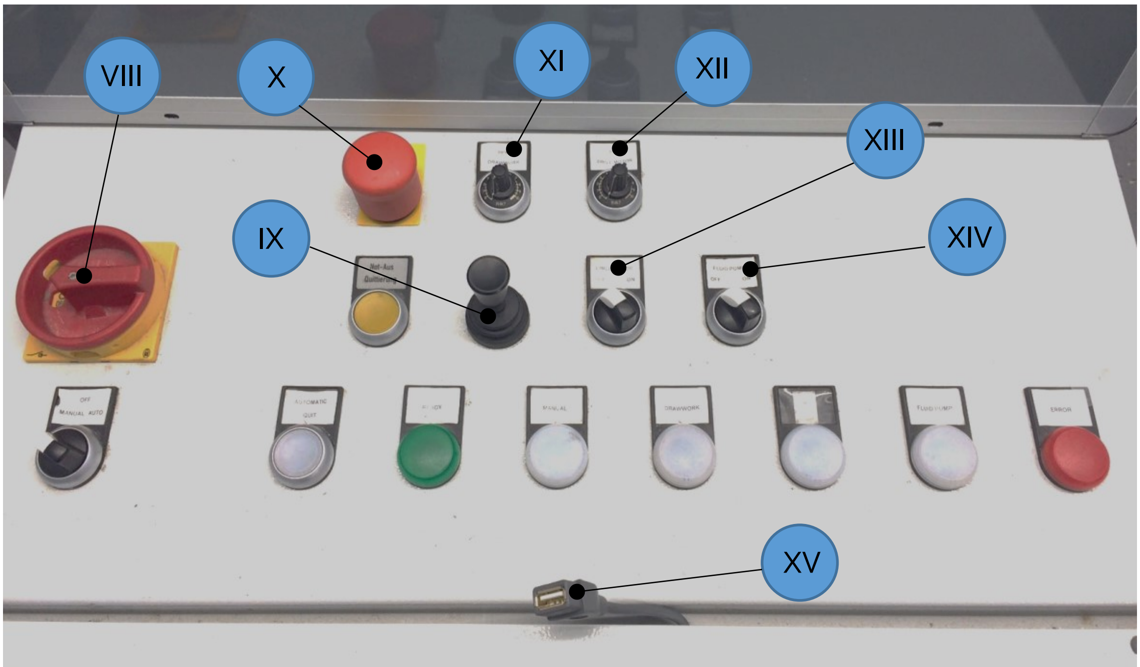


Figure 41: Central control unit

To ensure safety, an emergency stop switch (X) is also part of the installation. The control device has also a switch to regulate the drawworks RPM (XI). This is a very important feature for the experiment, since too high pulling speeds will cause contamination of the cement plug and hence influence the compressive strength of the plug negatively. By changing the drawworks RPM, different drillstring pulling speeds can be simulated and compared with the predicted critical speed of the decision tree program. In case that the top drive system is installed a separate switch (XII) can be used to control the RPM of the drill motor. Switch (XIII) turns on/off the drill motor and switch (XIV) turns on/off the fluid pump which pumps drilling mud or water though a separate hose and the top drive down to the drill bit. To extract the data that was collected by the sensors attached to the rig (e.g. hook load, block position, WOB…) a separate USB port (XV) is provided by the control unit.

6.1.2 Upper Part- Pump and Manifold

During a cement plug job in the field, different fluids are present in the wellbore. Beside the drilling mud, which is used to stabilize the borehole, cool the bit or transport cuttings to the surface a viscous plug base fluid is pumped into the well. The plug base fluid is used to provide the base for the cement in case that no bridge plug can be used (e.g. if the well must be side-tracked in an open hole section). Finally, spacer fluids and the cement slurry are pumped downhole and landed on the viscous fluid. In order to simulate plug operations as realistic as possible in the laboratory, also different fluids are pumped during the experiment. To do so, a custom-build manifold including the pump and a fluid reservoir is designed by the author of this thesis and finally connected to the surface hose (4) of the mini-rig system. Figure 42 shows a picture of the special designed manifold.

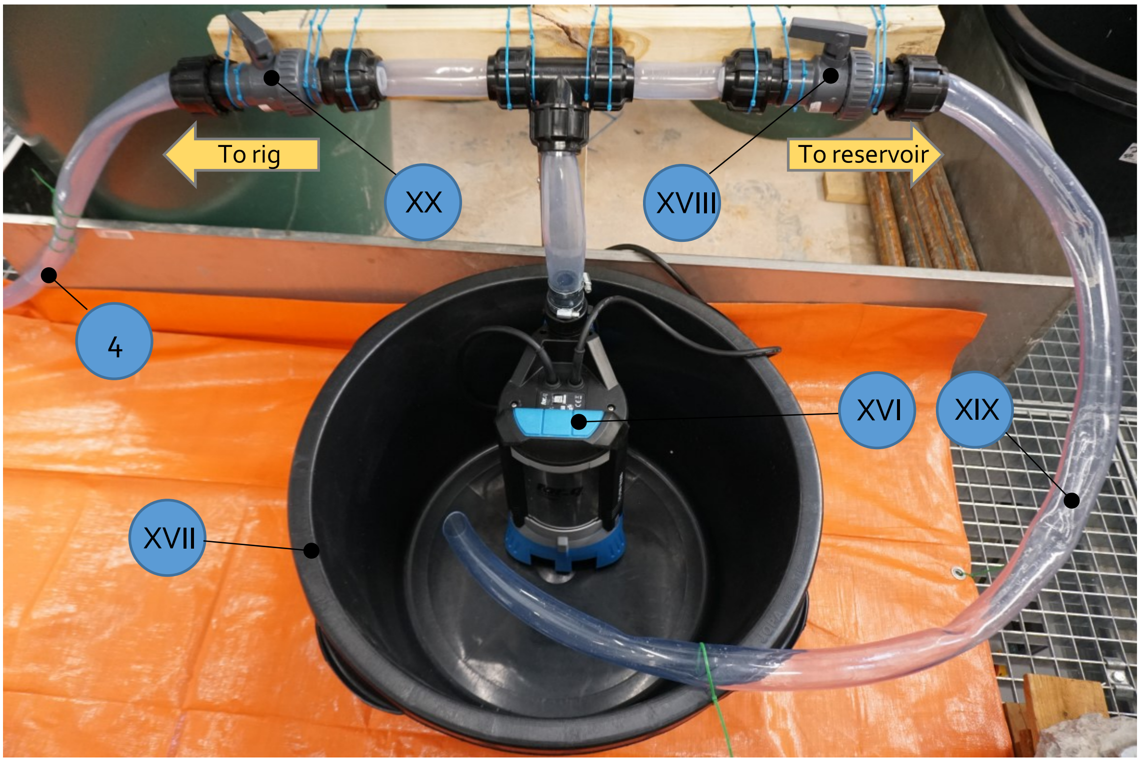


Figure 42: Custom-build manifold with fluid pump and reservoir container

The fluid pump (XVI) is a sewage pump with a maximum feed rate of 18.500 litres per hour. Because of the pump specifics to operate in a dirty environment also small fines and particles (up to 35mm grain size) can be handled by the pump. This allows the user to pump all kind of drilling fluids and cement slurries without changing the pump type. The feed for the pump is stored in the reservoir container (XVII) with a capacity of 50 litres. The pump itself has no adjustable flowrate. The volume that is pumped to the wellbore can only be controlled indirectly by using the different valves on the manifold. Valve (XVIII) is used to open or close the return loop (XIX) to the reservoir. Valve (XX) adjusts the flowrate to the hose (4) that is connected via the swivel to the Plexiglas stinger.

Before the pumping operation starts, valve (XX) has to be closed by 100%. Valve (XVIII) must be open at least 50%. This combination allows the fluids to be pumped via the sewage pump (XVI) and return line (XIX) back into the reservoir (XVII) once the pump is switched on. It also helps to fill up the pump's intake area and the feed lines completely prior pumping to the wellbore. Furthermore, it hinders an uncontrolled flow into the rig hose (4) or even damage of the pump. Once the pump and feed lines are filled with fluid and pumping pressure has established, valve (XX) can be opened slowly and the return valve (XVIII) closed. This will guide the flow to the hose and consequently to the stinger pipe down the wellbore. When the desired volume is placed in the wellbore, the main valve (XX) has to be closed and simultaneously the return valve (XVIII) opened. Finally, the pump is switched off and the operation finished. Before a new fluid type is pumped, the system has to be flushed with clean water to ensure no unwanted contamination in the flowlines.

6.1.3 Lower Part- The Wellbore

As already mentioned in the previous section, the circumstances in the new laboratory allowed the installation of a complete drilling rig set-up including the simulation of a drilled wellbore. Figure 37 represents an overview of the set-up, where the lower part is located in the cellar of the laboratory. Figure 43 gives a more detailed view of the downhole installation. The drilled borehole (12) is represented by a Plexiglas tube of bigger size than the stinger pipe (7). The borehole pipe is placed and fixed in a metal frame (14). The frame is a custom-build scaffold that is especially designed by the author of this thesis for the experiments. The goal is, to invent a structure that also can be used for further simulations and experiments.

The borehole Plexiglas pipe is placed in the support rack (14) of the structure. Eight screws (four in the upper and four on the lower part of the rack), fix the pipe safely in place during the experiments and avoid unwanted vibrations or movement of the simulated borehole. The upper part of the rack is pivoted on the framework. This design allows the simulation of a deviated borehole to investigate e.g. the influence of the boycott effect on the cement plug integrity. The framework of the scaffold consists out of two welded arm sets with a massive beam on the bottom respectively. The beams provide weight to the structure and guarantee a safe seat during the simulations. Two joints (one on each side respectively) connect the support rack with the arms of the scaffold. The joint connection allows a rotational movement of the cage when the pipe is installed. To keep the cage in a pre-defined angle (to simulate e.g. a deviated wellbore), one has to tilt the support rack. The position must be fixed by using the transom (15) in combination with the aluminium bolt (16) where the bolt has to be pushed through the desired borehole of the transom. The tilted cage will then rest on the bolt, simulating a deviated borehole. If the experiments require a vertical position of the wellbore (as it is indicated in Figure 43), the bolt has no function, but the support rack can be fixed by using the L shaped profile welded on the beam of each arm. The lower part of the support rack is connected via a screw to the profile which keeps the scaffold in a safe and immobile vertical position.

If one of the experiments is finished and all parameters are evaluated, the used borehole pipe has to be replaced by a new one. To do so, one must tilt the rack in a horizontal position. On the one hand this will help to pour out the drilling fluid on top of the Plexiglas tube (the light drilling fluid is displaced upwards by the heavy base fluid and cement during the experiment) and on the other hand it facilitates the exchange of the tubes because of the more comfortable position. The rope (17) assists during the exchange process. It can be used to tilt the rack into the horizontal position and finally keep it in that attitude.

The polycarbonate wall (18) provides additional safety during the experiment. If one of the pipes burst because of unwanted movement or pressure shocks or because of a construction fault, all fluids should stay within the area that is bordered by the glass. Lab equipment and installations as well as persons that are present in the cellar are protected from the fluids. In addition, a drain tray (19) installed on the cellar floor collects the borehole fluids if a pipe bursts in order to avoid contamination of the laboratory.

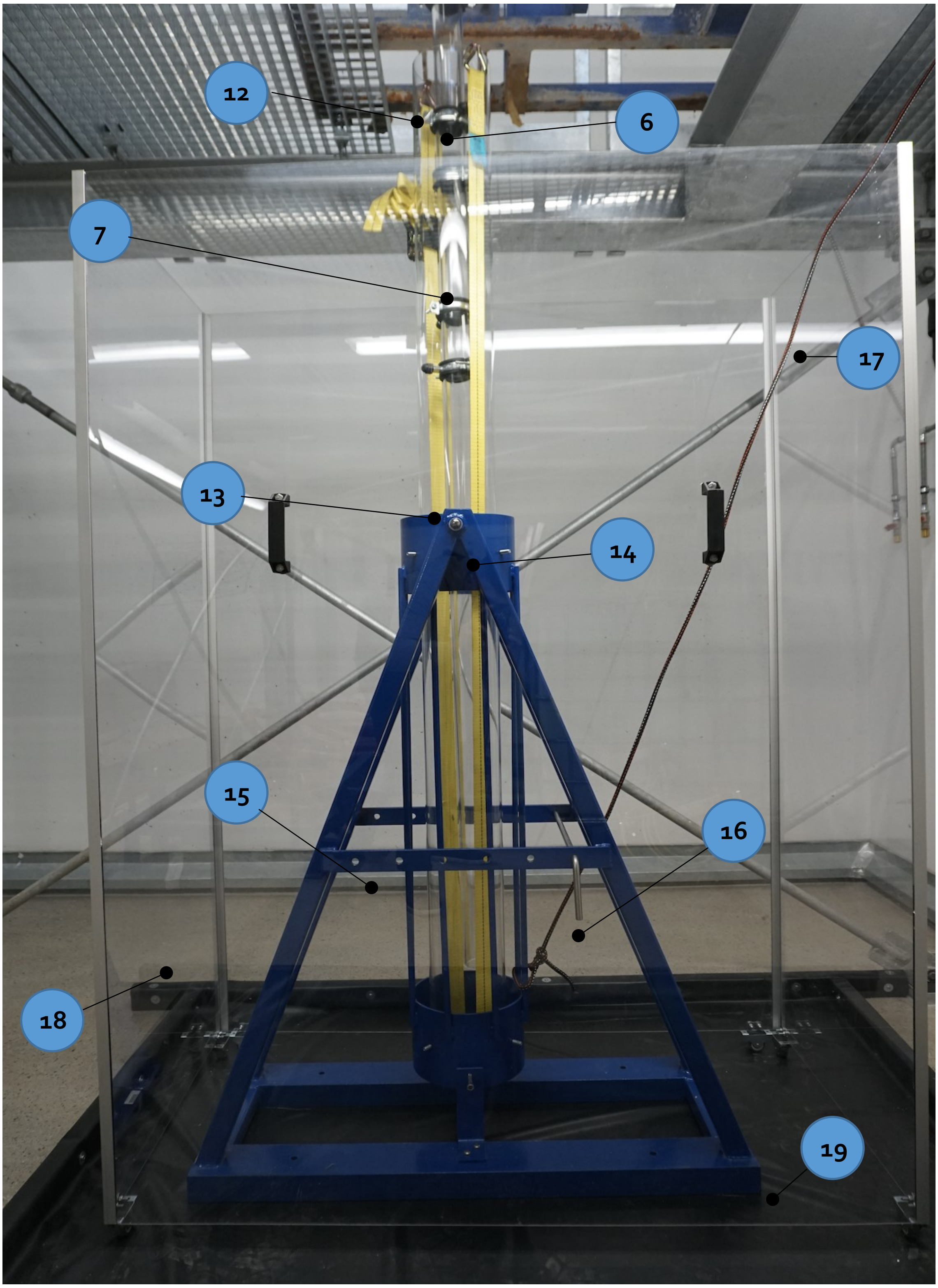


Figure 43: Lower part of the set-up (borehole)
The picture shows the lower part of the set-up which is located in the cellar. The stinger pipe (7) with attached centralizers (6) is placed in the borehole (12). To keep the borehole pipe under compression, an additional webbing load restraint assembly (13) is attached. The borehole pipe is placed and fixed in the metal frame (14) and can be tilted using the pre-drilled holes (15) and the steel bar (16) to simulate a deviated well. The rope (17) assists during borehole pipe change and can be used to fix the frame in a horizontal position. A polycarbonate wall (18) and a drain tray (19) are installed for safety reasons and to avoid spills.

6.1.4 Borehole Pipe and Stinger Pipe

The planning phase of the experiments pursued the goal, that all procedures and processes should be visible during the execution of the experiments in order to recognize typical effects such as a plug contamination or slumping of the slurry immediately, rather than during the plug recovery phase when everything is already static. To do so, it was decided to use transparent hoses as well as a transparent drillpipe/ stinger and a transparent wellbore for all experiments.

To simulate cement plug operations in the laboratory as much realistic as possible also typical wellbore to stinger ratios are chosen. The borehole pipe shows a diameter of 150 mm (5.9 inch) and the drillpipe has a diameter of 56 mm (2.2 inch). This ratio allows a realistic laboratory-based simulation of a cement plug job operation under downscaled field conditions. A kick-off plug set under such conditions corresponds to a real cement plug set in a 311 mm (12 ¼ inch) wellbore with a 127 mm (5 inch) sized drillpipe. Figure 44 shows a drawing of the borehole and stinger pipe combination used in the laboratory. The wellbore is simulated by the 150 mm (5.9 inch) Plexiglas tube. One end of the wellbore is closed with a special cap that fits exactly onto the pipe. The cap is also made of Plexiglas and mounted with a special acrylic glass glue on the borehole. To increase the contact area of the glue between the pipe and the cap, an additional lip is milled on the cap. The lip has the same size as the wall thickness of the wellbore pipe, so that the inner part of the cap fits exactly into the pipe and the outer part- the lip, sits tight on the borehole. Tests conducted with water showed, that the glue is strong enough to hold the cap on a completely fluid filled pipe- not only when the pipe is in the framework but also during the recovery phase. This is an important feature since the wellbore will be lifted from the cellar to the ground floor after the cement plug is set and cured in order to be evaluated and examined. During the lifting phase, the complete wellbore pipe will hang in the air without any additional support on the base. Therefore, it was necessary to test the performance of the glue in the forefront to avoid an unwanted snapping of the cap from the pipe resulting in a massive spill on the lab floor. Every borehole pipe will be used only once and must be replaced before the next test starts. The smaller pipe, that can be seen in Figure 44 represents the drill pipe that is used to pump the different fluids (drilling fluid, base fluid and cement slurry) downhole. Literature recommends the installation of a diverter tool in case that a cement plug is landed on a base fluid (R. C. Smith 1984). The stinger used in the experiments of this thesis is open ended, and not designed as a diverter pipe. This construction type simulates more unstable fluid interface conditions during pumping phase because the liquids fall directly on each other. As a result, the predicted output parameters of the software are tested under a harsher environment. In case that the open-ended stinger tests are successful, diverter-based stinger operations will be successful anyway. To ensure a centred position of the drillpipe, four additional centralizers are attached on the pipe body. After pumping all fluids into the wellbore, the stinger will be pulled with different speeds in order to simulate contamination of the cement slurry.

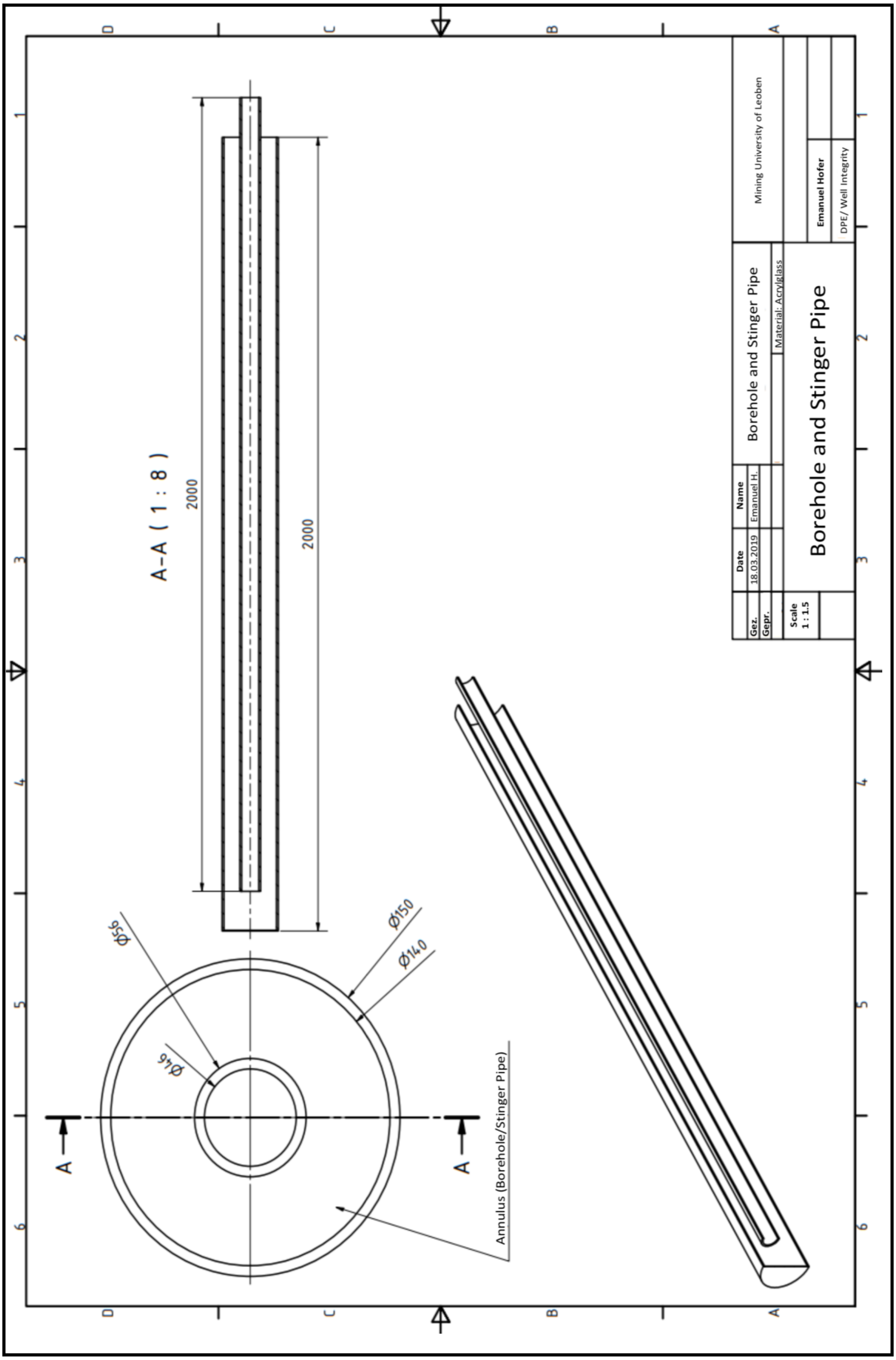


Figure 44: Sketch of the borehole/stinger combination for the simulations
The bigger Plexiglas tube represents the borehole and the smaller tube simulates the drillpipe/stinger that is used to pump the fluids (drilling mud, plug base fluid and cement)

6.2 Cement Plug Simulations

The following chapter describes the preparation of the different fluids which are used for the simulation of the cement plug jobs as well as a closer description of each simulation run including preliminary work steps, measuring procedure and execution- and examination phase. In total four different simulations are conducted where different parameters such as fluid densities, fluid yield stresses or pipe pulling speeds are changed. Prior preparation and execution phase, all cement plug jobs are designed with the excel based software. The outcomes of the program and the simulations are compared afterwards to check for the prediction dependability of the software.

Three different fluids are pumped downhole. As a first step the water-based drilling fluid is pumped via stinger pipe into the wellbore. This should simulate a hole drilled with this type of mud. Afterwards the base fluid is placed at the bottom of the wellbore. The weighted fluid should provide the base for the cement. The density difference between the drilling mud and the base fluid displaces the mud upwards. During the final step, the prepared cement slurry is pumped via the drillpipe into the wellbore and landed on the base fluid. Volume calculations showed that in total 30 litres of fluids (10 litres of drilling mud, base fluid and cement slurry respectively) can be pumped downhole. This corresponds to 120 cm (47.24 inch) of fluid height and finally a theoretical 60 cm (23.6 inch) cement plug. The upper most 20 cm (7.87 inch) of the 2 m (78,74) tall borehole pipe are calculated as a safety area if more than 10 litres of one fluid is pumped downhole.

6.2.1 Drilling Mud

The fluid that simulates the drilling mud in the wellbore is a conventional potassium carbonate mud. Such water-based polymer muds are widely used in the oil and gas industry, especially in areas where potassium chloride is prohibited because of environmentally reasons (e.g. Austria). When drilling shale formations, carbonate muds provide stability to the formation, reduce swelling tendency of the shale and minimize dispersion of clay particles.

The base recipe for the mud looks as follows:

• Potassium Carbonate (K_2CO_3)	80 kg/m^3
• S-ES Bio XG	4 kg/m^3
• S-ES Pac LV	14 kg/m^3
• Citric Acid	1 kg/m^3

Figure 45 shows a picture of the ingredients that are used for mixing the water-based drilling mud. S-ES Bio XG is a xanthan gum that is used as a viscosity agent. S-ES Pac LV is a fluid loss agent and citric acid is used for pH control of the mud. The drilling fluid recipe stays the same for every simulation. Density as well as rheological properties will not change and are measured only once. The mud is prepared 24 hours prior job execution. For mixing the fluid, all ingredients are weighed carefully and added separately to the water to prohibit clumping of the additives (Figure 46).

Figure 45: Ingredients for the water-based K_2CO_3 drilling mud

Figure 46: Preparation of the drilling mud

The mixed drilling mud shows following properties (Table 6):

Density					
1055 kg/m^3- 8.8 ppg					
Rheology					
ϑ_{3}	ϑ_{6}	ϑ_{100}	ϑ_{200}	ϑ_{300}	ϑ_{600}
7	9	20	33	50	78
10 sec. gel			**10 min. gel**		
7			8		
pH					
11.37					
Resistivity					
0.15 Ωm					

Table 6: Lab measured properties of the drilling mud

The yield stress of the polymer mud can be evaluated by using the measured rheological properties (ϑ_{300} and ϑ_{600}). The calculated yield stress is 4.6 Pa or 22 lb/100 ft^2.

6.2.2 Plug Base Fluid

The base fluid is a densified drilling mud that provides the base for the cement slurry. Typically, such viscous pills are used for sidetracking open hole wellbores, where the application of bridge plugs are not feasible. The base fluid used for the simulations in this thesis is a conventional bentonite mud. The bentonite mud is mixed 24 hours prior job execution to provide sufficient time for the development of rheological characteristics. The base recipe for the mud schedules 80 g of bentonite per liter of water. This value might be high for conventional drilling muds but will be sufficient for the application as a cement plug base fluid.

All simulations require different base fluid properties. To increase the density of the mud, barite will be added to the system. The mathematical calculation for the right quantity of barite needed in order to reach a designated base fluid density can be seen in equation [28].

$$B = \left[\frac{35.05 * \left(W_f - W_s\right)}{35.05 - W_f}\right] * V_s \qquad [28]$$

Where:

- B → Amount of barite required [lbs]
- V_s → Starting volume of mud [gal]
- W_f → Desired mud weight [ppg]
- W_s → Starting mud weight [ppg]

The barite is added in small batches to the mud and mixed for several minutes until a smooth and homogenous base fluid is obtained. Depending on the simulated wellbore conditions, base fluid density and yield point will be adapted for each run. To increase the yield of the fluid a special temperature resistant starch is used as the right additive. Figure 47 shows the basic ingredients for the viscous pill. Since each simulation requires different base fluid characteristics, all important properties (rheological qualities and densities) are measured separately for each simulation run. The corresponding table can be found in the description of the particular run.

Figure 47: Ingredients for the plug base fluid
Bentonite is in the left beaker and water in the right measuring jug. The barite in the front is used as a weighting agent to increase the density of the mixed base fluid.

6.2.3 Cement Slurry

The cement slurry is the centerpiece of each plug job operation. The right property selection and preparation of the slurry but also a correct placement of the cement in the wellbore adjudicates upon success or failure of the job. The cement used for setting the plugs in the simulations of this thesis is a special oil well cement from Dyckerhoff. The Dyckerhoff Class G- Black Label is an API certified Class G Grade HSR (High Sulphur Resistant) oilfield cement that provides all kind of well cement properties which are demanded by the oil and gas industry. The preparation of the cement slurry is executed, after the drilling mud and the base fluid are pumped into the wellbore. Prior preparation, all ingredients (water, cement and additives) are measured carefully. The quantity of cement that is necessary in order to prepare a 10 litre slurry with a particular density is calculated using the equation suggested by API 10-B regulation (equation [29]). In some simulation runs it is necessary to increase the yield of the slurry. To do so, temperature resistant starch is used and mixed to the cement during preparation phase.

$$V_w = \frac{1000 * \left(1 - \frac{\rho_s}{\rho_c}\right) - \sum\left[V_{ad.liq.} * \left(\rho_s - \rho_{ad.liq}\right)\right] + \sum\left[m_{ad.sol.} * \left(1 - \frac{\rho_s}{\rho_{ad.sol.}}\right)\right]}{\left(\rho_s - \rho_w\right)} \qquad [29]$$

Where:

- ρ_s → Density of the slurry
- ρ_c → Density of the cement
- $\rho_{ad.liq}$ → Density of the liquid additives
- $\rho_{ad.sol.}$ → Density of the solid additives
- ρ_w → Density of the mix water
- $m_{ad.sol.}$ → Solid additive mass
- $V_{ad.liq.}$ → Liquid additive volume
- V_w → Required volume of the mix water

6.2.4 Simulation 1

6.2.4.1 General

The first simulation produces a cement plug that is set in the vertical part of a wellbore. According to the literature, vertical set kick-off plugs often suffer from density problems between the base fluid and the slurry (R. C. Smith 1984; J. Heathman and Carpenter 1994). The yield difference of the fluids has only a minor influence on the success rate and can normally be neglected. This is why the design program asks for the density difference rather than for both, the density and the yield of the fluids when designing a vertical plug on the paper. The goal of this simulation is the investigation of the influence of the density difference between the fluids as well as the impact of a high pulling speed of the stinger pipe. To do so, a vertical set cement plug with a low density difference between the base fluid and the slurry (according to the literature a stable base should be achieved) and a relatively high pulling speed of the drillpipe is designed. Due to the high pulling speed, contamination is expected in the upper part of the plug.

6.2.4.2 Fluid Parameters

The drilling mud specifics are listed in Table 6 and stay the same for every simulation. The measured base fluid characteristics as well as the cement properties can be seen in Table 7 and Table 8.

Density					
1246 kg/m^3- 10.4 ppg					
Rheology					
ϑ_3	ϑ_6	ϑ_{100}	ϑ_{200}	ϑ_{300}	ϑ_{600}
53	55	85	105	120	160
10 sec. gel			**10 min. gel**		
54			60		
pH					
9.19					
Resistivity					
10.14 Ωm					

Table 7: Lab measured properties of the base fluid for the first simulation

The measured yield stress of the base fluid is 16.7 Pa or 80 lb/100 ft^2 and relatively high. This is because 80 gram of bentonite per liter of water is used in the recipe. For a drilling mud this might be a high number but for the use as a base fluid it is an optimal value. The mud is mixed 24 hours prior job execution.

Density					
1306 kg/m³- 10.9 ppg					
Rheology					
ϑ_{3}	ϑ_{6}	ϑ_{100}	ϑ_{200}	ϑ_{300}	ϑ_{600}
2	3	4.5	6	8	11
10 sec. gel			**10 min. gel**		
2			2.5		

Table 8: Lab measured properties of the cement slurry for the first simulation

The calculated yield of the cement slurry is 1.04 Pa or 5 lb/100 ft². The slurry is relatively thin because of the high water content in order to reach the low density (1306 kg/m³ or 10.9 ppg).

6.2.4.3 Predicted Design Parameters of the Program

Using all fluid parameters described in Table 6, Table 7 and Table 8 as input variables for the excel based software following results were predicted (Table 9):

Slurry volume needed	
10.23 litres	
Predicted interface stability	
Density difference OKAY	
Pressure drop req. to erode mud	**Pressure drop generated**
0.0035 bar	0.0052 bar (@ 0.31 m³/min pump rate)
Critical velocity cement	**Induced annular velocity**
0.7 m/sec	2.78 m/sec. (@1.0 m/sec. pulling speed)
Induced swab pressure	**Flow regime cement**
7140 Pa	Turbulent (@1.0 m/sec. pulling speed)

Table 9: Software predicted design parameters for the first simulation

6.2.4.4 Laboratory Simulation

For executing the simulation, all tools and auxiliary means described in chapter 6.1 are used for this run. In a first step, the stinger is connected to the drawworks of the rig and lowered into the wellbore. After running in hole (RIH) the prepared drilling mud is pumped via manifold and the transparent hose downhole (Figure 48a). Before the next batch is placed in the well the drilling mud is left for one hour in the borehole. This allows the mud to apply gel strength and to recover from the shear forces applied by the pump. In the meanwhile, the pump is flushed and cleaned with water and the base fluid prepared for the next step. The base fluid is pumped in the same manner as the drilling mud into the well where the bentonite pill displaces the lighter drilling mud upwards (Figure 48b). In a next step, the stinger pipe is pulled upwards, between the interface of the base fluid and the drilling mud. For balancing the cement plug, the pipe is kept in this position. During the first simulation run it turned out that the lower end of the transparent drillpipe can be recognized very hard because of the cloudy appearance of the polymer mud (Figure 49a). The lower edge of the stinger pipe blurs in the mud and can only be spotted very poorly. As an improvement for all other simulations, three stripes of a durable black duck tape are attached on the lower side of the pipe. This helps to spot the end of the pipe much better in the cloudy mud and one can be sure that the cement is landed on the base fluid and not in the bentonite pill (Figure 49b).

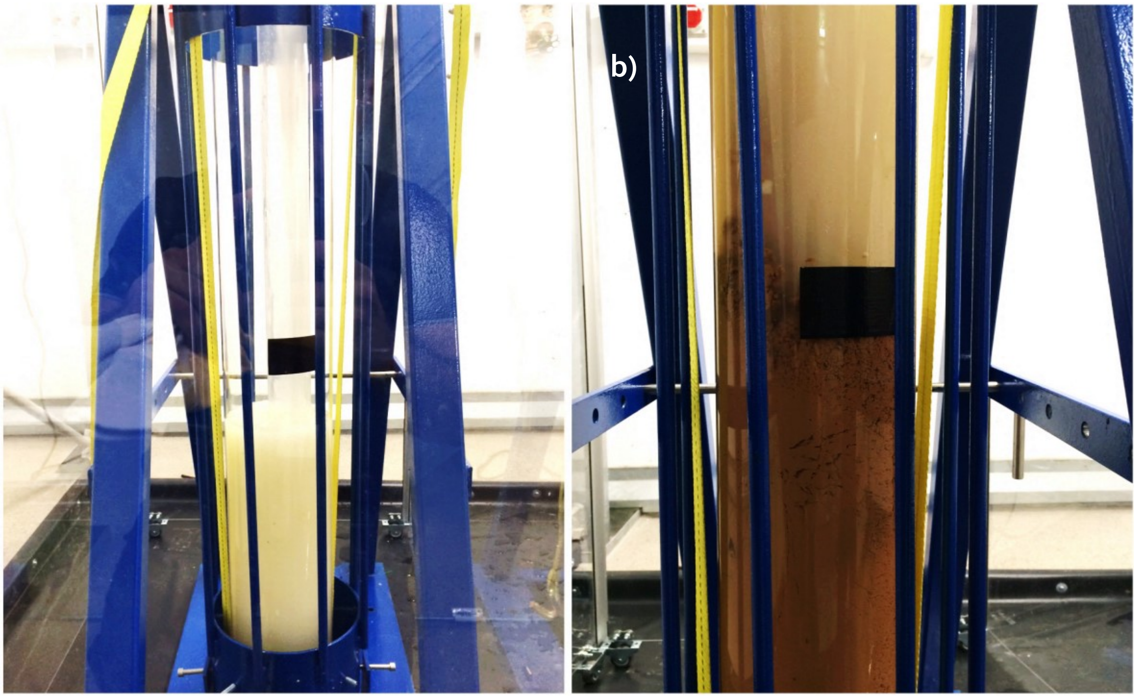


Figure 48: Pumping of drilling mud (left) and base fluid (right)

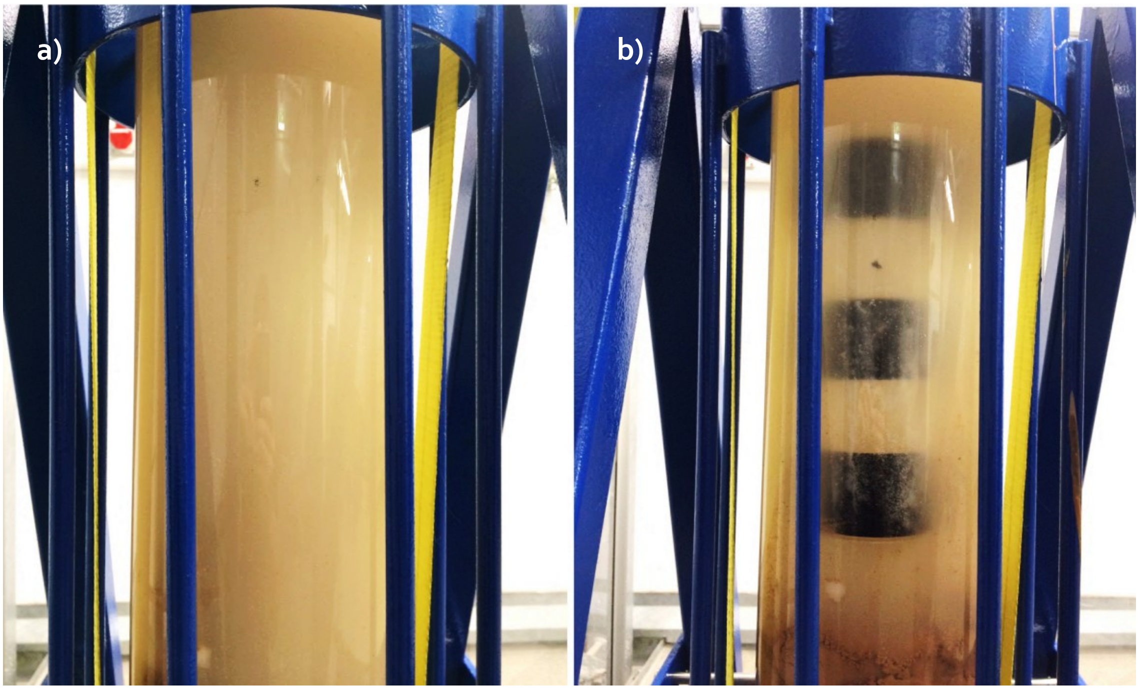


Figure 49: Improvements on the stinger equipment

In a next step, 10 litres of cement slurry are mixed. For adapting the density of the slurry close to the measured density of the base fluid (the software predicts a stable interface) 8549 grams of mix water and 4572 grams of cement are used (for calculating the right quantities, equation [29] is applied). In the end a slurry density of 1306 kg/m^3 or 10.9 ppg is measured. After slurry preparation, the plug is balanced above the base fluid. Therefore, the cement is pumped via the manifold, the transparent hose and the stinger tube downhole. After landing the plug on the viscous pill, the drillpipe is pulled out of hole (POOH). During plug job operations conducted in the field, this part is one of the most critical steps in terms of contamination of the cement slurry. The stinger in the lab is pulled with 1.6 m/sec. According to the prediction of the software, this speed will induce an annular velocity of 2.78 m/sec. and therefore exceed the critical tripping speed of the designed slurry (0.70 m/sec.). As a consequence, a turbulent flow regime will be induced in the cement which should result in a contamination of the plug. During the last step of the run, the stinger tube is recovered from the wellbore and cleaned from slurry deposits. Furthermore, surface equipment (pumps, mud) are prepared for the next simulation. After approx. 24 hours of curing time, the drilling mud is poured out from the pipe (to reduce weight) and the complete wellbore recovered from the cellar (Figure 50).

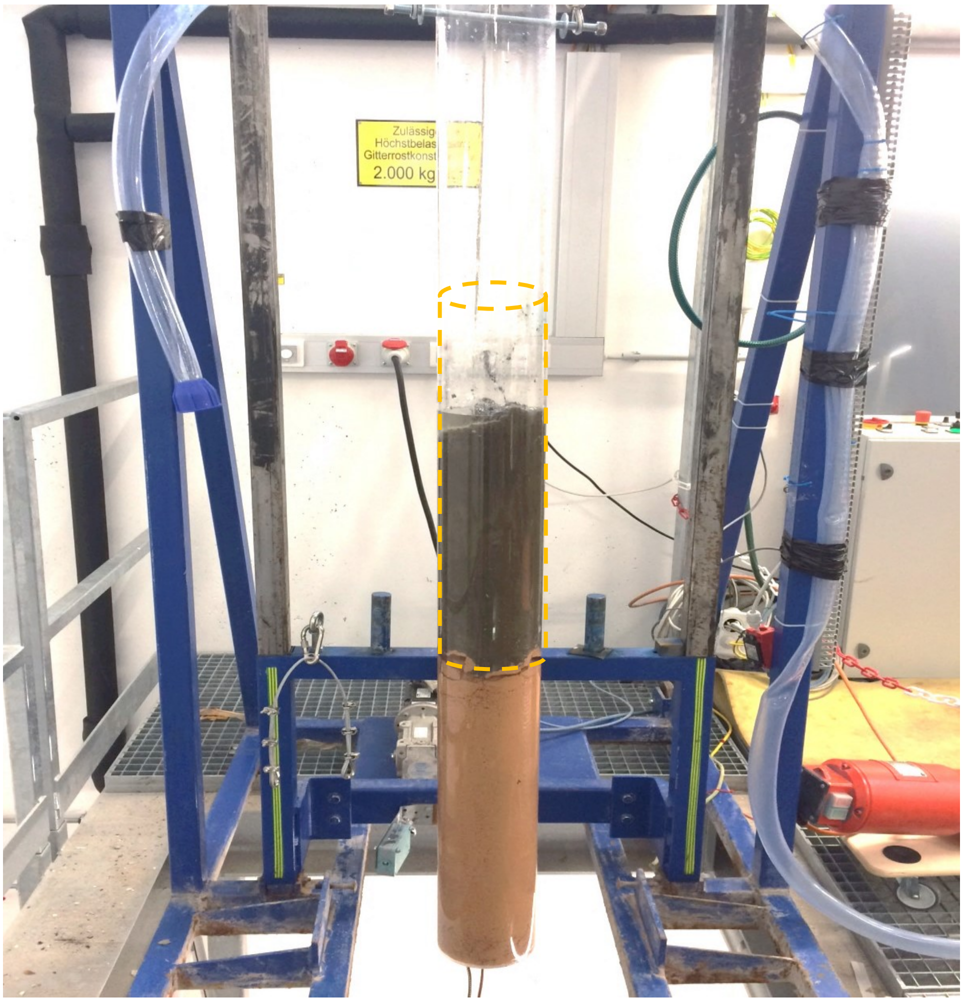


Figure 50: Recovery of the kick-off plug using the drawworks of the drilling rig
The dotted cylinder indicates the initial panned cement plug height. The loss of the upper part is due to contamination with drilling mud during stinger pulling operation.

6.2.4.5 Visual Observation and Findings

During the pumping procedure of the drilling mud and the base fluid, no distinct abnormalities could be observed. The heavy bentonite fluid displaced the lighter mud upwards and a sharp transition between both liquids was visible. Also, no abnormalities could be monitored during cement pumping job. A visual check of the slurry/base fluid interface showed that the density difference between both fluids was small enough so that the cement could float on the viscous pill without any problems. Checking the plug after pulling the stinger out of hole showed that part of the cement slurry was dragged into the drilling fluid. The entrained slurry formed cords and seemed to mix with the polymer mud (Figure 51). During recovery phase of the plug (after 24 hours) it could be observed, that the contamination was substantial. The majority of the upper part of the cement slurry did not cure and could be poured out of the pipe along-with the drilling fluid (Figure 50). The intended top of the plug will not be reached since the contaminated slurry will not set.

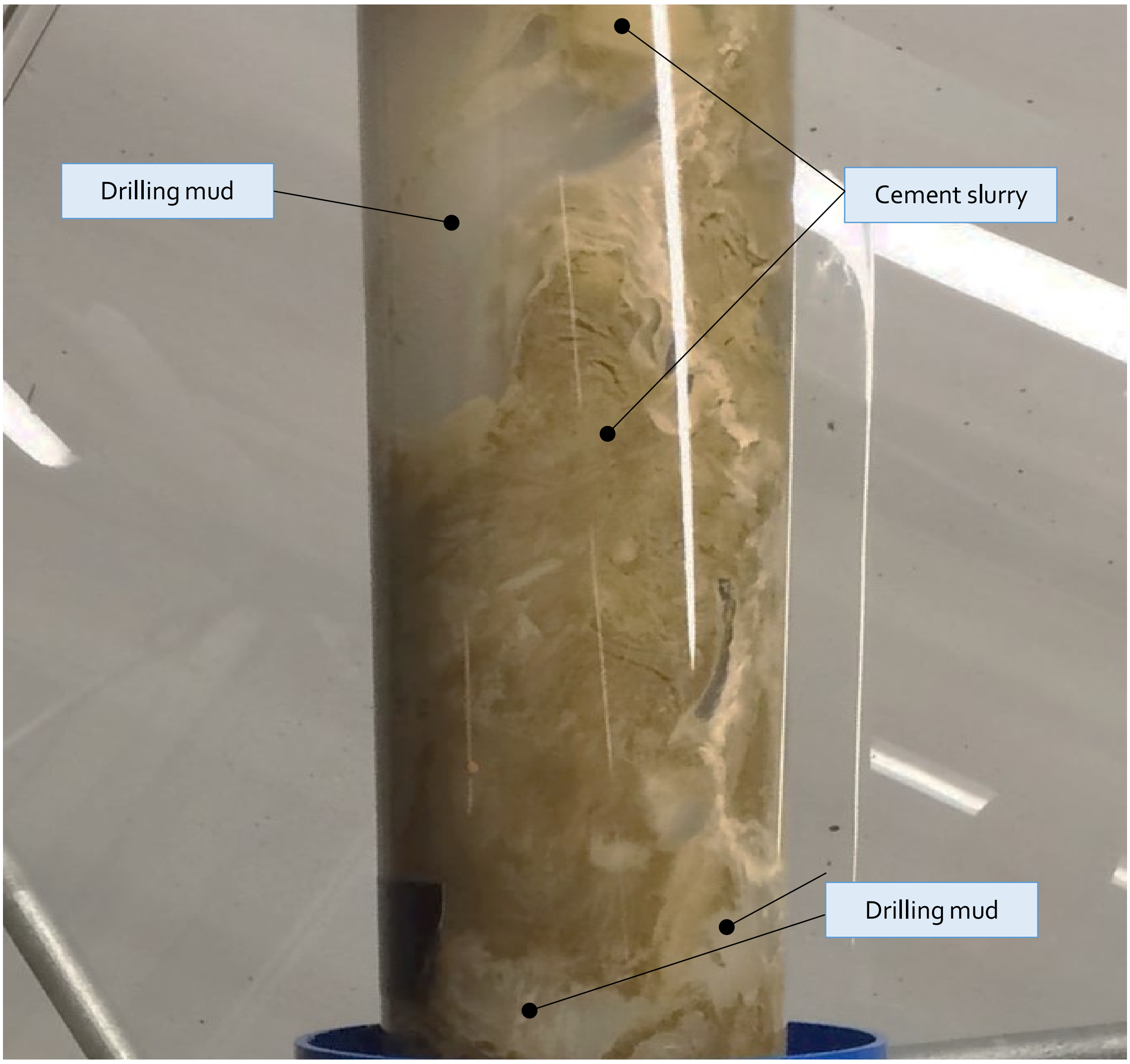


Figure 51: Contamination of the cement slurry during pulling operation
The picture shows the moment when the stinger pipe was pulled from the cement. The high tripping speed caused a turbulent flow in the cement resulting in a massive contamination of the slurry with the polymer mud. As a consequence, approx. 40% of the plug was lost and did not cure after 24 hours.

6.2.4.6 CT Interpretation

In the following, the computer tomographic imaging interpretation of the first simulation is explained in more detail. The scan is conducted in the laboratory of Reservoir Engineering where a new CT scan is used to analyze e.g. core samples. The medical CT is normally built for hospitals to investigate divergences in human bodies. Due to the same nature of a human body and the cement plug (fluids imbedded in between a denser material) the medical CT is an appropriate tool in order to analyze the kick-off plugs. Figure 52 shows the first plug before scanning.

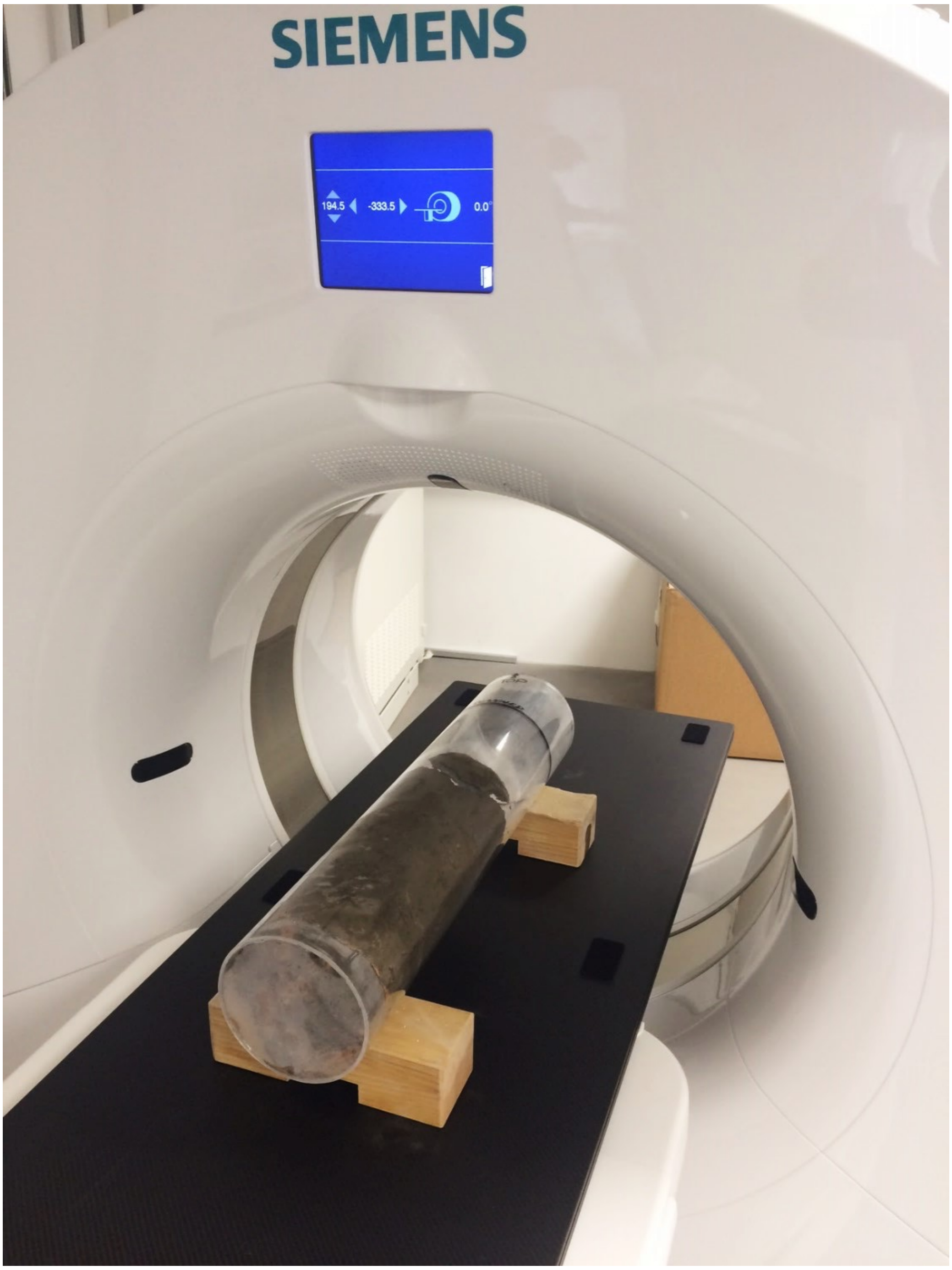


Figure 52: Cement Plug No. 1 prepared for CT scanning
The picture shows the first kick-off plug, prepared for scanning in the CT. The Plexiglas pipe is the original one from the simulation. Drilling fluid and base fluid are removed.

The images are analyzed using a program called Avizo®. Figure 53a displays the complete scanned cement plug in a 3D view and Figure 53b shows the same vertical plug from the front. The plug is cut in the middle to illustrate inhomogeneities and discrepancies.

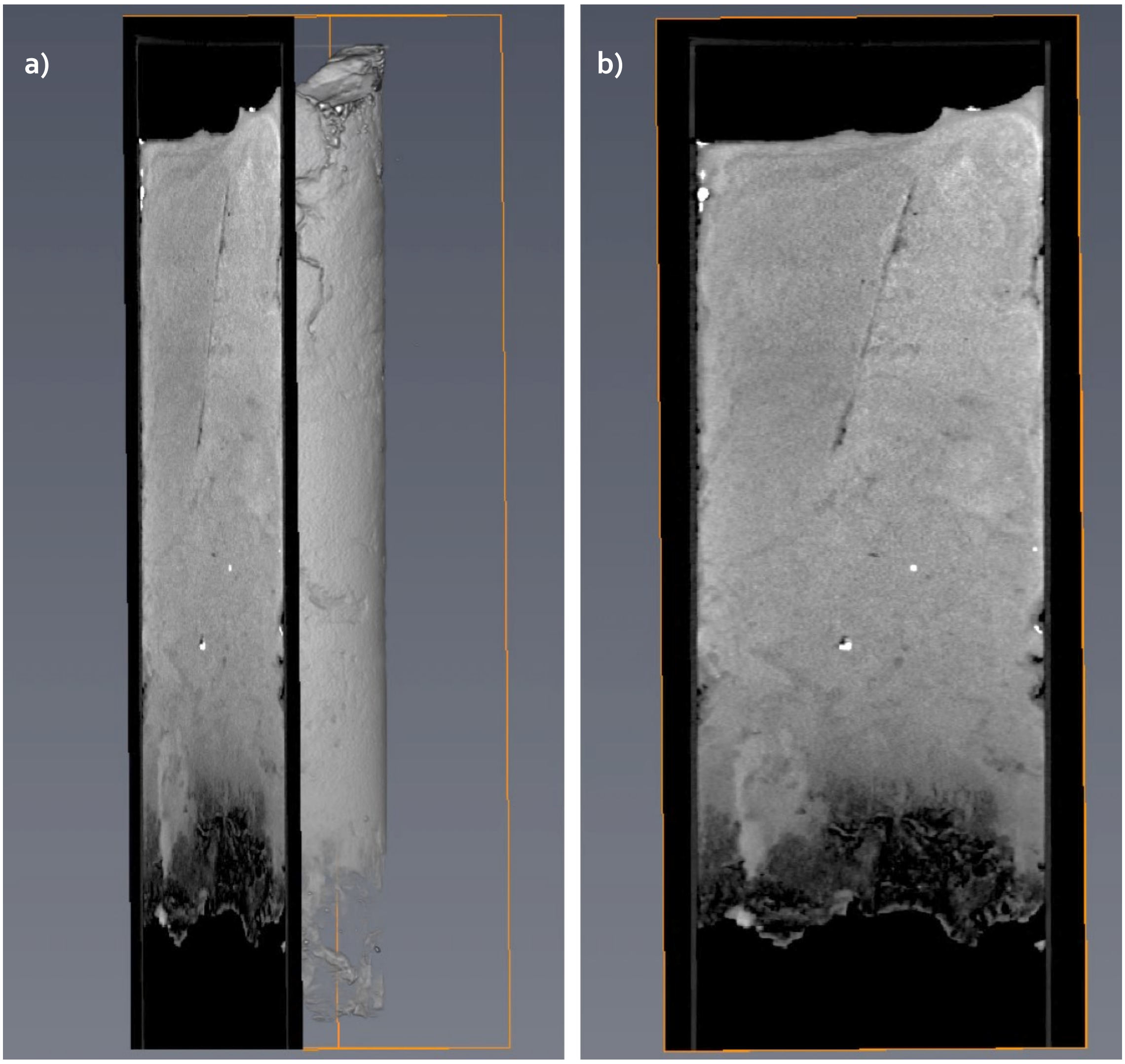


Figure 53: Scanned plug No. 1 in 3D view (left) and front view (right)
The picture shows the scanned plug. The light grey colour indicates pure cement, the black one on the bottom shows a more compacted cement slurry.

Figure 53a and Figure 53b displays the total length of the plug. The interpretation of the scanned pictures indicates a very homogenous cement mass. The light grey part is an evidence for pure cement with same density. The black segment at the bottom of the plug shows a denser structure. This might be due to gravitational forces that triggered the compaction of the slurry at this part of the plug. Since nearly all contaminated cement left the pipe when the drilling fluid was poured from the tube, no contamination is shown. The sharp demarcation between the bottom of the plug and the base fluid (the base fluid is already removed for the scan) indicates a very stable plug base. The result also confirms the outcome of the software that predicted a stable interface due to a sufficient small density difference between both fluids. To investigate the cross-sectional quality of the plug, three particular locations within the plug are selected. The overview of the position as well as the specific slices are shown in Figure 54a-d.

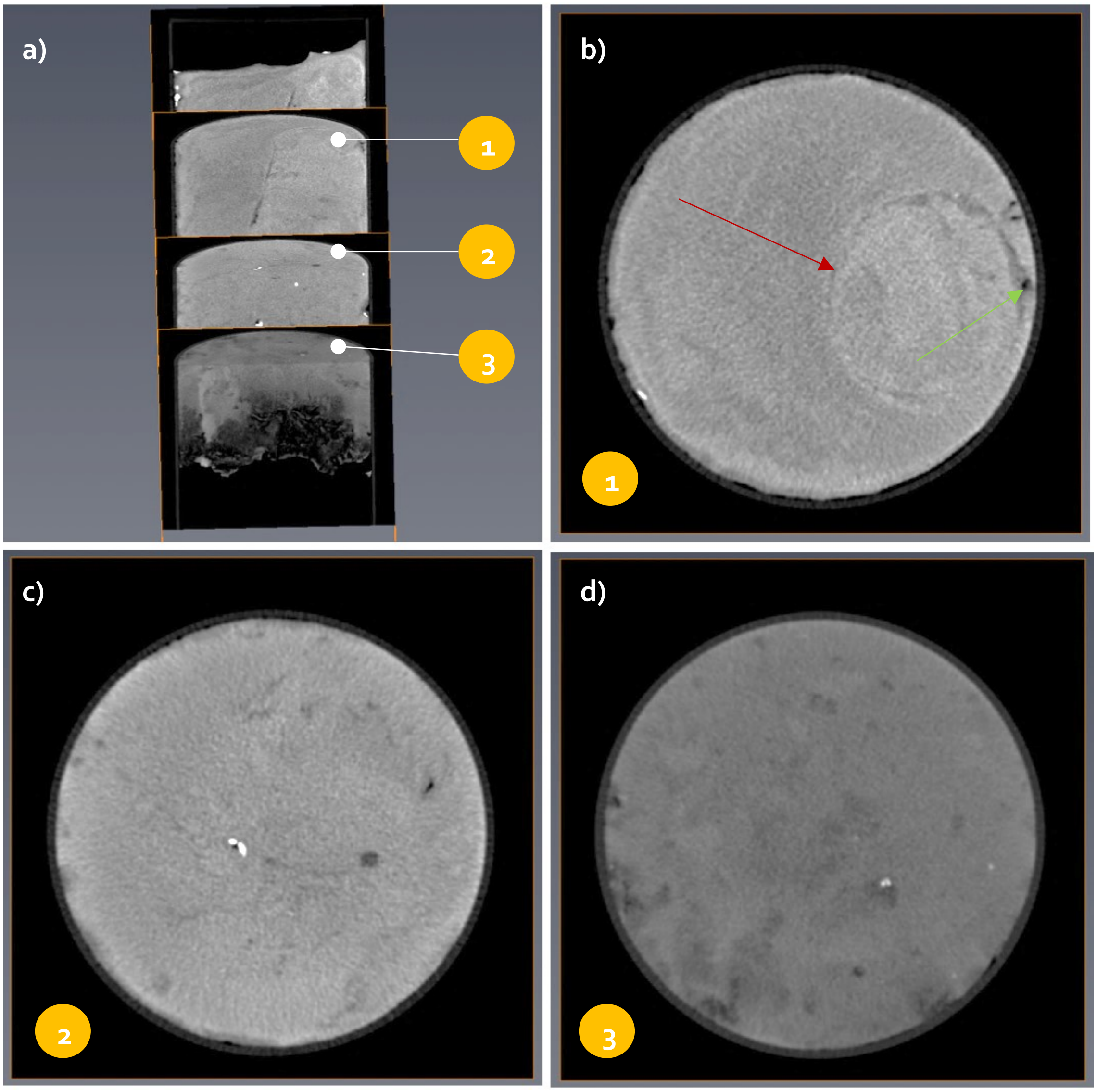


Figure 54: Cross sectional interpretation of plug 1
Three individual slices (1-3) are cut from the scanned plug. One on top (1), one in the middle (2) and one at the bottom (3) of the plug.

The interpretation of the slices shows no distinctive divergences. One interesting feature that can be observed in Figure 54b is the position of the stinger pipe (indicated by the red arrow). It seems that the pulling of the pipe induced a change in the homogeneity of the cement slurry. The scan clearly shows the initial position of the pipe including the pipe wall (denser area) and the filling (lighter area). It might be the case that after pulling, the void of the stinger Plexiglas wall was filled by a mixture of slurry and some drilling fluid. Due to the decentralization of the pipe during slurry placement, some drilling mud might has entered the void from the boundary area at the right (indicated by the green arrow) after pipe pulling operation. Figure 54c and Figure 54d are not indicating such a ring structure. This is because the end of the drillstring was placed above the selected points (c and d). In total it can be stated, that the cement plug (at least the fraction that is left after pouring the drilling fluid from the pipe) is very homogenous. No prominent divergences are monitored. The stinger "ghost" shown in Figure 54b has no indicational influence on the overall integrity of the plug.

6.2.4.7 Comparison of Software and Simulation Results

The laboratory simulation was conducted with the same parameters which were used for the software prediction. The results of the software are listed in 6.2.4.3. To set a 60 cm tall plug, 10 litres of cement slurry are pumped downhole. The base fluid to plug interface is very stable. After pouring the viscous pug base fluid from the pipe, a nearly perfect transition zone was observed. The cement in this area is hard and cured. The exceeding of the predicted critical velocity for the cement slurry resulted in a massive contamination of the upper part of the plug. Approximately 40% of the cement plug is lost because of the contamination. The CT interpretation confirms the predicted stable slurry to base fluid interface.

6.2.4.8 Conclusion

The prediction of the software is very accurate. The predicted vertical interface stability could also be achieved in the laboratory simulation. The CT results confirm a stable interface showing a sharp transition between the cured cement and the base fluid. The tripping speed was too high in order to generate a successful kick-off plug since nearly 40% of the plug is lost due to contamination. In the field, this plug probably would have failed to sidetrack the wellbore at the designated location. The software predicted turbulent flow as well as a too high tripping speed. This could be verified with the first simulation run. CT imaging interpretation showed a homogenous cement mass within the complete remaining plug. No distinctive divergences are observed. The stinger ghost has no measurable influence on the plug integrity. In total it can be stated, that the remaining plug has a homogenous structure and might be able to apply the compressive strength that is needed in order to kick-off from that wellbore. The kick-off point is lower than expected since a large portion of the plug is lost due to contamination.

6.2.5 Simulation 2

6.2.5.1 General

The second, as well as the third and fourth simulation runs are conducted in order to test and simulate plugs jobs executed in deviated boreholes. Such kick-off plugs often suffer from boycott effect issues or instable fluid interfaces resulting in slumping of the cement slurry through the plug base (4.1.3). As a consequence, parts or even the total cement plug is lost, and the job must be repeated. In contrast to vertical cement plugs where the density difference between the base fluid and the cement is crucial, deviated kick-off plugs are also influenced by the yield characteristics of the different fluids. The simulation is performed to test the prediction quality of the software in terms of interface reliability in inclined wellbores. To do so, a kick-off plug with a high density difference between the base fluid and the slurry and a moderate pulling speed is designed. The base fluid has a moderate and the cement a low yield point. According to the prediction of the software a very instable interface should occur (Figure 62). As a consequence, the cement should fall through the base and create a failed plug. The wellbore should be kicked off at 35° inclination.

6.2.5.2 Fluid Parameters

The drilling mud specifics for the second simulation run are listed in Table 6. The measured base fluid characteristics as well as the cement properties can be seen in Table 10 and Table 11.

Density					
1222 kg/m^3- 10.2 ppg					
Rheology					
θ_3	θ_6	θ_{100}	θ_{200}	θ_{300}	θ_{600}
51	53	82	100	115	155
10 sec. gel			**10 min. gel**		
52			69		
pH					
9.15					
Resistivity					
10.05 Ωm					

Table 10: Lab measured properties of the base fluid for the second simulation

The measured yield stress of the base fluid is 15.7 Pa or 75 lb/100 ft^2. The density of the bentonite pill is not increased in order to generate a high density difference between the slurry and the base. For the fluid also 80 grams of bentonite per liter of water is used. The mud is mixed 24 hours prior job execution.

Density					
1785 kg/m³- 14.9 ppg					
Rheology					
ϑ_3	ϑ_6	ϑ_{100}	ϑ_{200}	ϑ_{300}	ϑ_{600}
8	13	21	29	43	55
10 sec. gel			**10 min. gel**		
-			-		

Table 11: Lab measured properties of the cement slurry for the second simulation

The measured density of the cement slurry is 1785 kg/m³ or 14.9 ppg. The density corresponds to standard slurries typically used in drilling operations. The calculated yield of the cement slurry is 6.47 Pa or 31 lb/100 ft².

6.2.5.3 Predicted Design Parameters of the Program

Using all fluid parameters described in Table 6, Table 10 and Table 11 as input variables for the excel based software following results were predicted (Table 12):

Slurry volume needed	
10.23 litres	
Predicted interface stability	
Instable interface	
Pressure drop req. to erode mud	**Pressure drop generated**
0.0035 bar	0.0052bar (@ 0.31 m³/min pump rate)
Critical velocity cement	**Induced annular velocity**
1.52 m/sec	1.66 m/sec. (@ 1.0 m/sec. pulling speed)
Induced swab pressure	**Flow regime cement**
10135 Pa	Turbulent (@ 1.0 m/sec. pulling speed)

Table 12: Software predicted design parameters for the second simulation

6.2.5.4 Laboratory Simulation

For executing the simulation, all tools and auxiliary means described in chapter 6.1 are used for this run. In a first step, the stinger pipe is connected to the drawworks and hook of the rig and lowered into the wellbore. After running in hole (RIH) the prepared drilling mud (the mud is the same for every simulation) is pumped via manifold and the transparent hose downhole (Figure 48a). Prior pumping the next fluid, the mud is left for one hour static in the borehole. During this time, the mud applies the required gel strength. In the meanwhile, the pump is flushed and cleaned with water and the base fluid prepared for the next step. After placing the base fluid in the wellbore, the stinger is raised to the designated cement plug location. Due to the improvements done on the transparent drillpipe (Figure 49), a clear indication of the right position is now possible. One goal of this simulation run is the identification of the influence of a heavy cement slurry on a lighter base fluid in an inclined wellbore. According to the prediction of the software, an instable fluid interface should be formed (Figure 62). Therefore, 10 litres of the prepared 1785 kg/m^3 14.9 ppg cement slurry are pumped downhole. For the slurry, 6323 grams of mix water and 11582 grams of neat Class G cement are used (for calculating the right quantities, equation [29] is applied). After balancing the cement on the viscous base, the stinger pipe is pulled with 1.0 m/sec. from the wellbore. According to the prediction of the software, this speed will induce an annular velocity of 1.66 m/sec. which is slightly higher as the calculated 1.52 m/sec. critical speed for the cement slurry. As a consequence, a turbulent flow regime is prevailing. The expected contamination should be smaller compared to the first run. After pulling the stinger pipe from the wellbore, the borehole is tilted approx. 35° to simulate an inclined wellbore (Figure 55). The tipping procedure of the borehole is conducted straight after the drillpipe is pulled from the well. Because of the small distance between plug location and surface installations and because of the inflexibility of the Plexiglas tubes, the stinger pipe must be pulled first prior tilting of the wellbore. The inclination hinders a smooth and uncomplicated drillpipe recovery because of constructional circumstances of the laboratory. After approx. 24 hours of curing time, the drilling mud is poured out from the pipe and the complete wellbore recovered from the cellar.

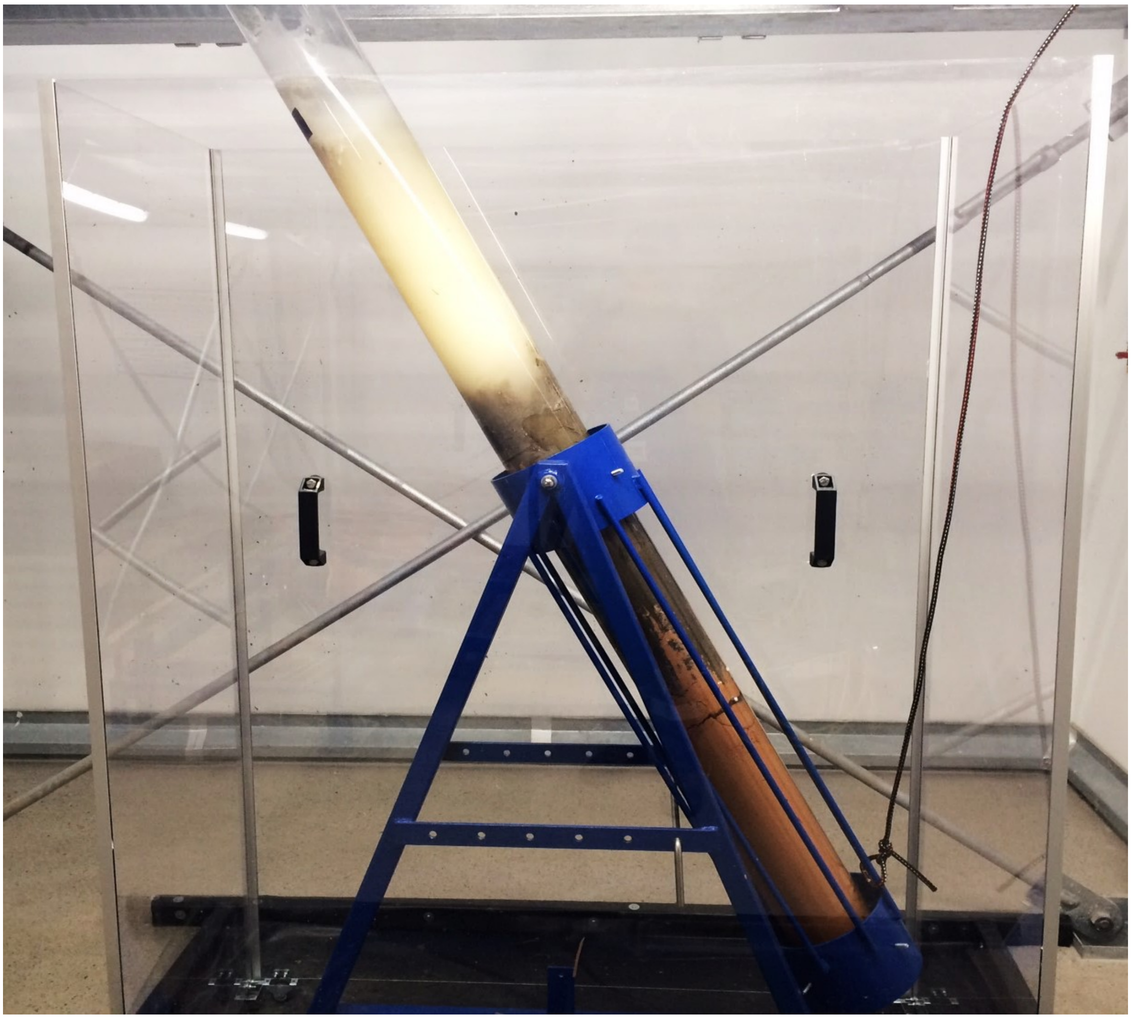


Figure 55: Cement plug No. 2 set in an inclined wellbore

6.2.5.5 Visual Observation and Findings

During the pumping procedure of the mud and the base fluid, no distinct abnormalities could be observed. The heavy bentonite fluid displaced the lighter mud upwards as expected. A sharp transition between both liquids was visible. Also, no abnormalities could be monitored during cement pumping job. Nevertheless, an abnormally was spotted after pulling the stinger tube from the slurry. Immediately, parts of the cement began to fall through the viscous plug base. At the beginning, the process was very slowly, but as soon as the wellbore was inclined, the process began to accelerate. The cement formed kind of fingers that crawled down the Plexiglas wall of the wellbore (Figure 56a). After 24 hours curing time, parts of the cement fell through the plug base fluid (Figure 56b). It also seemed that during pipe pulling operation, the dragging forces induced by the swab pressure carried some of the lighter base fluid into the cement matrix. Furthermore, the upper part of the initial cement plug mixed with drilling fluid and formed fluid pockets (Figure 57, Figure 58) but it could be observed that mud contamination was way smaller compared to the first run. Only little slurry escaped from the pipe when the mud was poured from the wellbore. Nevertheless, a simple compressive test with a screwdriver showed that the upper part was wet and not drillable after 24 hours of curing time.

Figure 56: Kick-off plug partly falling through the plug base
Figure 56a shows the cement slurry straight after tilting of the wellbore. Figure 63b shows the recovered kick-off plug after 24 hours of curing time. The slurry formed fingers and partly fell through the base fluid.

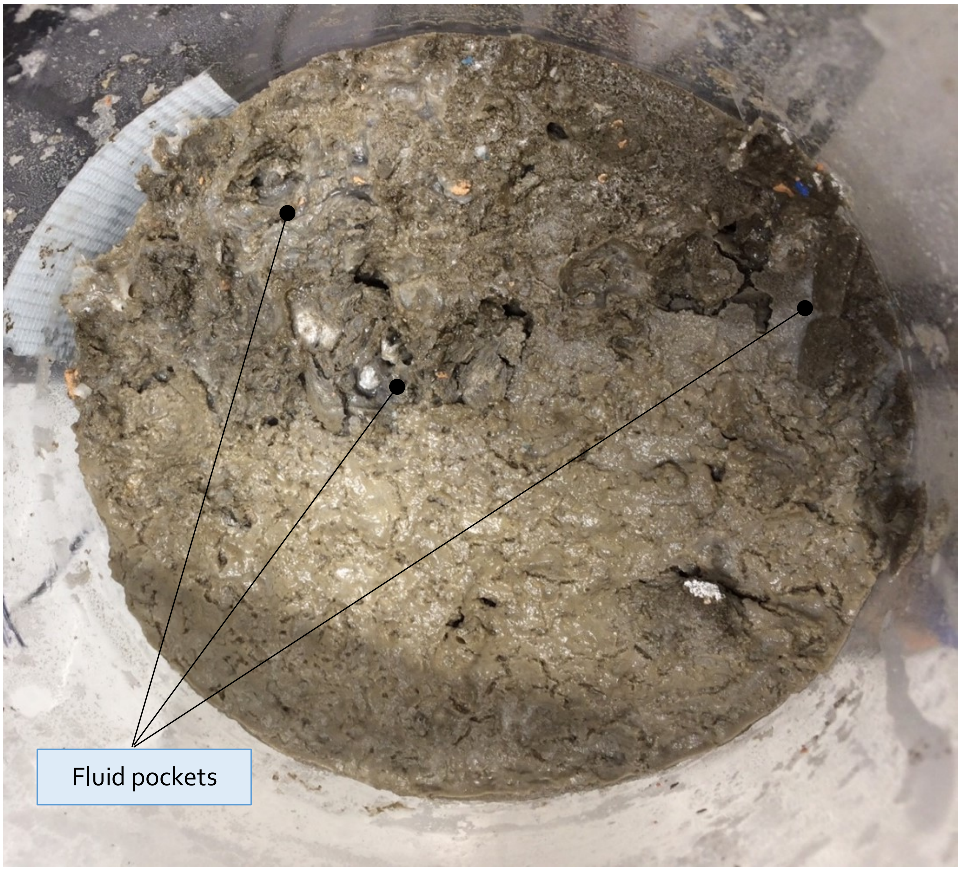


Figure 57: Mud pocket contaminated kick-off plug (top view)

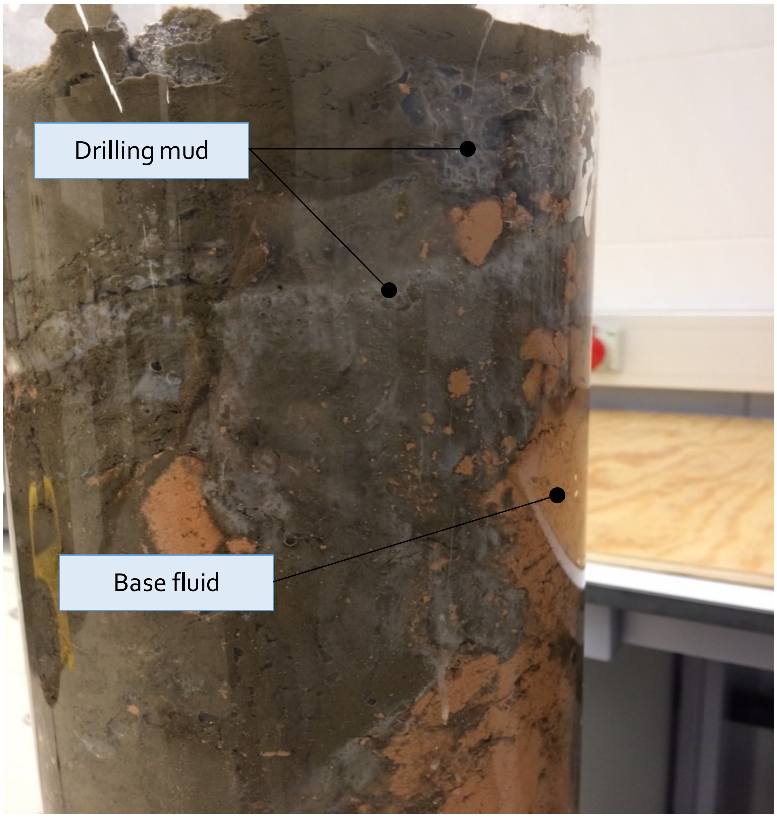


Figure 58: Contaminated cement plug (side view)
Cement contaminated with drilling mud (white fluid) and base fluid (brown liquid).

6.2.5.6 CT Interpretation

As already described in the previous chapter, the CT scan is conducted in order to investigate inhomogeneities within the cement matrix. Figure 59 shows the plug prior scanning process.

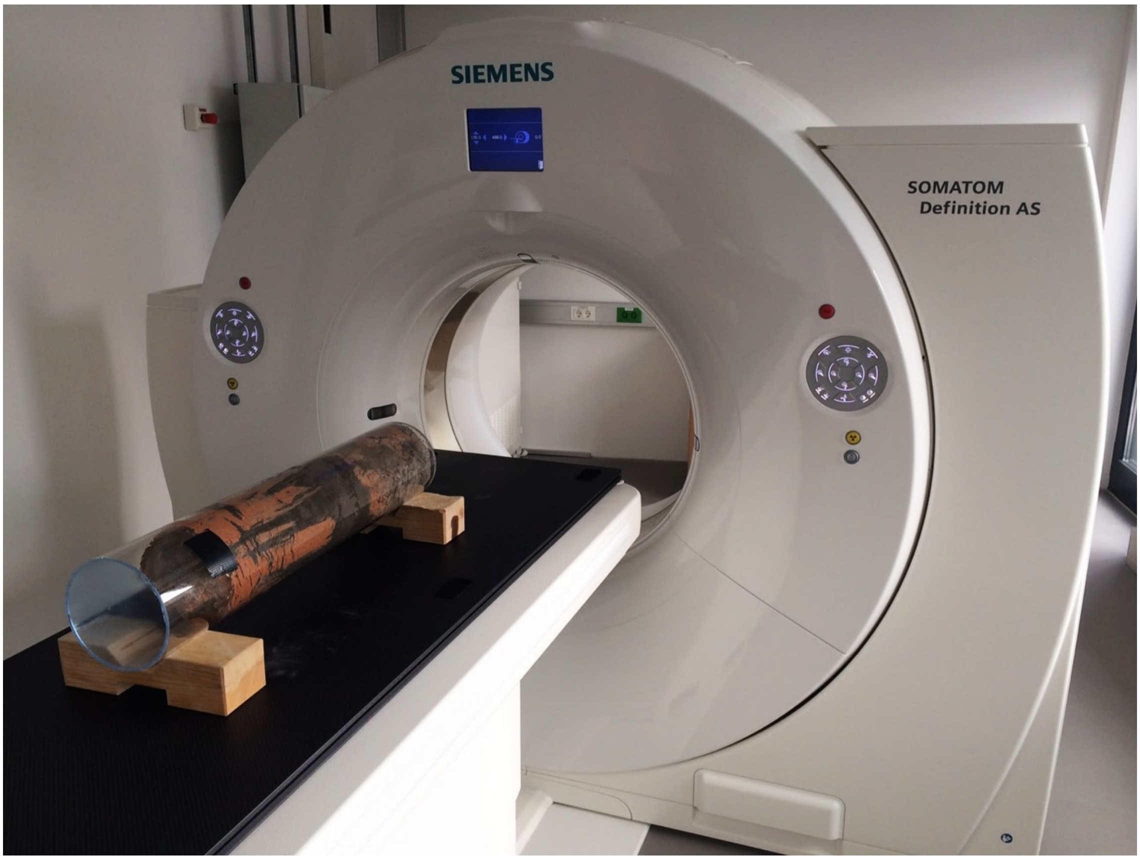


Figure 59: Cement Plug No. 2 prepared for CT scanning

After scanning process, the images are interpreted with the designated software. Figure 60a shows the complete scanned cement plug in a 3D view and Figure 60b shows the same deviated plug from the front. The plug is cut in the middle to illustrate inhomogeneities and discrepancies. The interpretation of the scanned plug indicates more heterogeneities compared to the first kick-off base in the previous chapter. Increased contamination is shown in the upper part of the plug, where a mixture of drilling fluid (dark spots) as well as cement (grey areas) and base fluid (white parts) are dominant. The cement and drilling fluid contamination in the upper most area of the plug is high (red arrow). The findings prove the visual observations described in chapter 6.2.5.5. The predicted turbulent flow regime caused a mixture of the slurry and the potassium carbonate mud and formed a kind of channel or chimney (green arrow). The observed mixture of the base fluid and the cement is also indicated in the CT scan. The swabbing forces carried some of the base fluid into the cement matrix leading to additional inhomogeneities in the upper part of the plug (yellow arrows). The white spots at the edges of the plug show some base fluid that was pushed upwards when some of the cement fell through the base. The lower part of the plug has a conical shape that indicates an instable interface. The void was filled with base fluid (white area at the bottom- blue arrow).

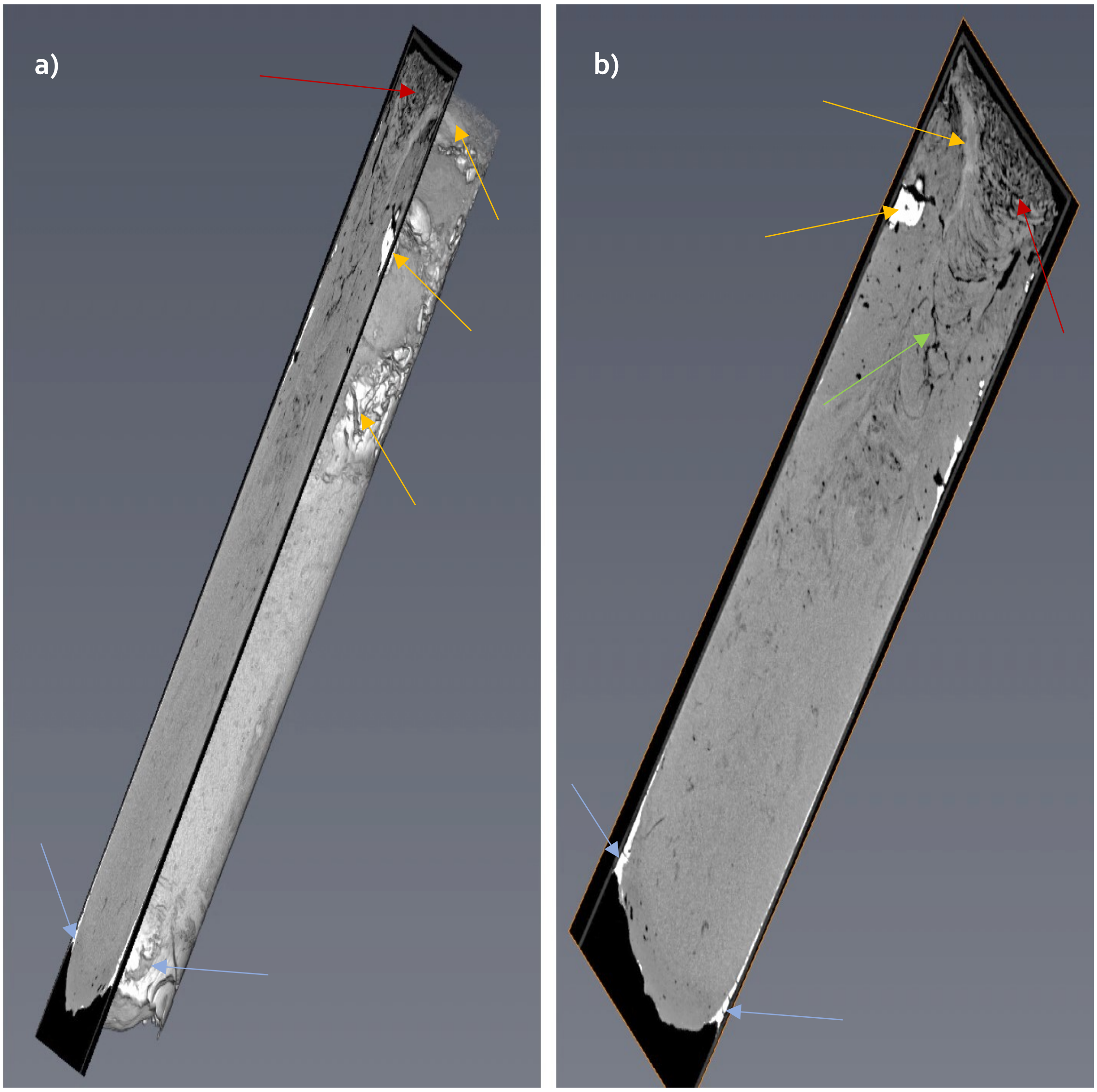


Figure 60: Scanned plug No. 2 in 3D view (left) and front view (right)

Beside the slurry contamination effects on the top and bottom, also a relative homogenous cement matrix is monitored in the middle part of the plug. This observation is surprising of one looks at the recovered plug (Figure 56b). The external attention would consider a complete contaminated cement through the whole length of the interval. However, the CT imaging indicates a very homogenous cement mass in the middle of the kick-off plug.

To investigate the cross-sectional quality of the second plug, four particular locations within the plug are selected. The overview of the position as well as the specific slices are shown in Figure 61a-e. The interpretation of the slices shows a major contamination in the upper third of the plug. Drilling fluid (black) is intermixed with cement (grey) and base fluid (white). The first slice (1) displays more or less a cement/ drilling fluid heterogeneity with some base fluid. This is a result of the turbulent flow regime and the selected pulling speed. Slice (2) shows a big fraction of base fluid (probably carried up by the induced swab pressure) and voids filled with drilling mud (black areas). Less drilling mud, but also base fluid contamination is observed in slice (3) whereas pure cement with only little base fluid is seen in (4).

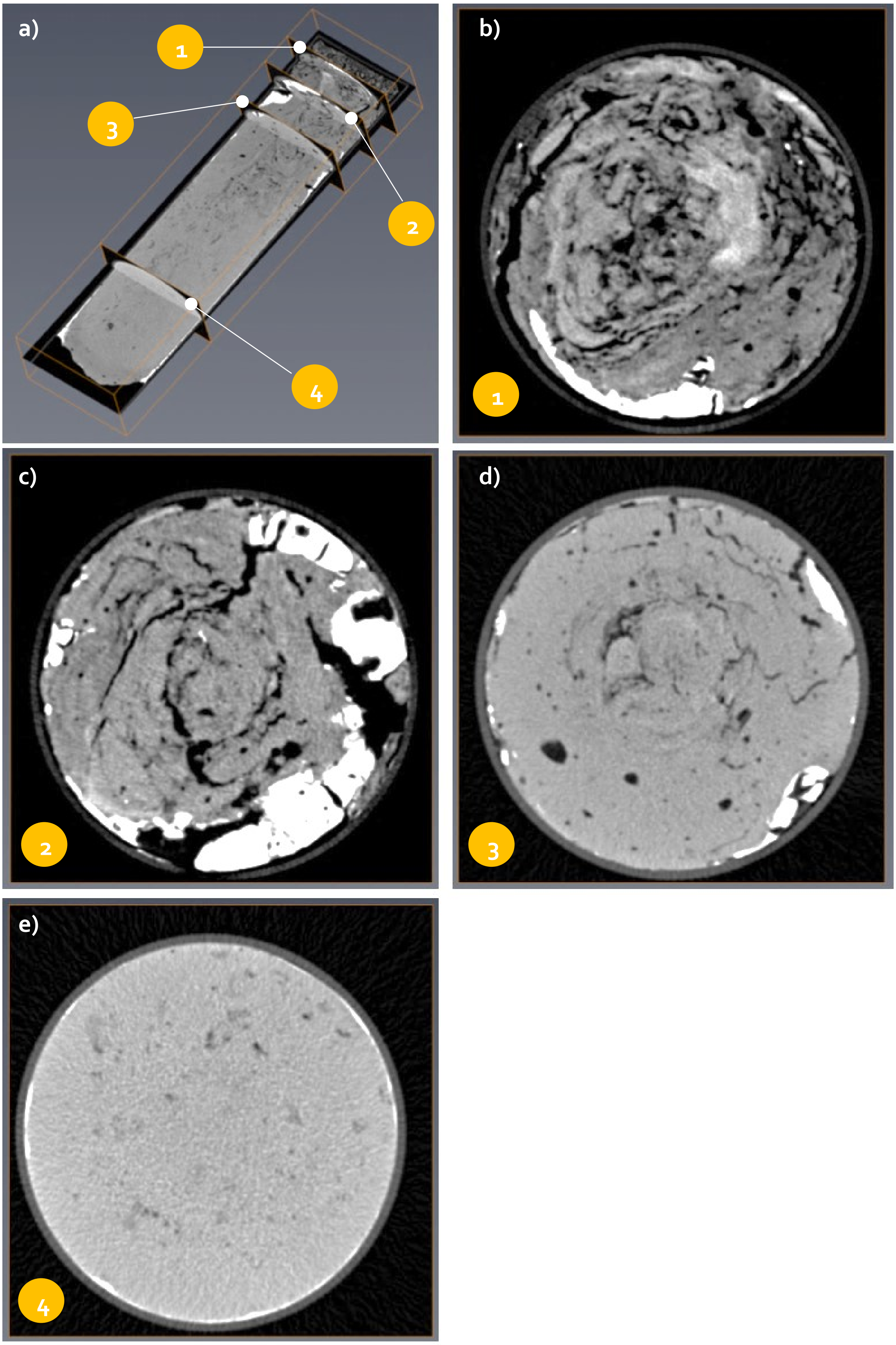


Figure 61: Cross sectional interpretation of plug 2
Four different slices (1-4) are cut from the scanned plug. Slice (1), (2) and (3) are displaying the top section and slice (4) the lower part of the plug.

6.2.5.7 Comparison of Software and Simulation Results

The laboratory simulation was conducted with the same parameters which were used for the software prediction. The results of the software are listed in 6.2.5.3. Figure 62 shows the predicted inclined interface stability plot generated by the program. The red cross clearly indicates, that the interface between the base fluid and the cement slurry is instable.

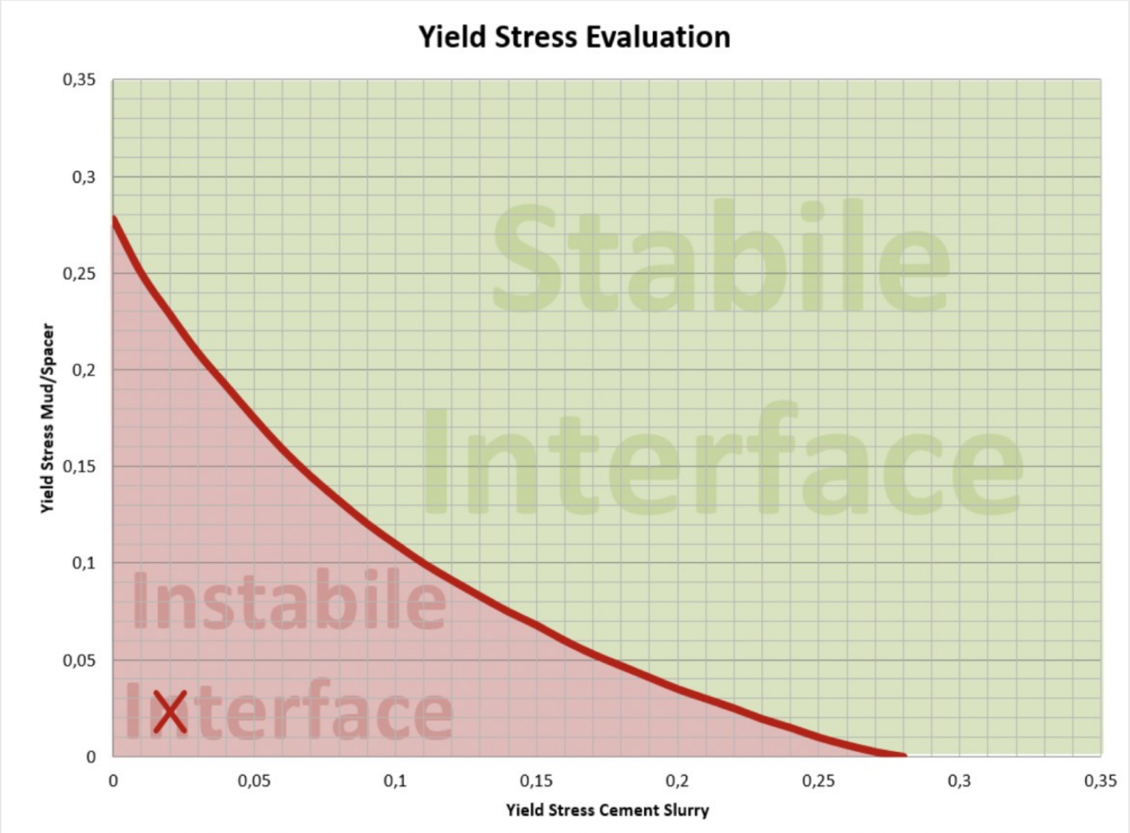


Figure 62: Interface stability plot for the second simulation (inclination 35°)

The experimental observed base fluid to cement plug interface was instable. The slurry formed viscous fingers that dragged along the wellbore wall. Therefore, the predicted outcome and the real interface behavior matched very well. The contamination as well as the instable base is also observed in the CT scan. A conic shaped bottom indicates that the heavier cement fell through the base, whereas the void at the wellbore wall was filled with the bentonite suspension. The program calculated a critical cement velocity of 1.52 m/sec and assumed an average annular velocity of 1.66 m/sec. The initiated swabbing pressure caused contamination of the slurry and the drilling mud. Furthermore, it seemed that the swabbing force dragged some of the base fluid into the cement matrix. The visual observed findings could be confirmed with the CT scan images. White spots of base fluid intermixed with grey cement and black islands of drilling mud. The prediction of the software is accurate and matches with the findings from the simulation run. Due to the listed design parameters, less cement to drilling mud contamination was expected in the forefront.

6.2.5.8 Conclusion

The evaluated design parameters of the software and the outcomes of the laboratory simulation agree in many points. The difference between the calculated annular velocity and the critical speed for the cement is much smaller compared to the prior conducted simulation run. The observed contamination is less and fewer cement left the pipe when the mud was poured from the wellbore. Using the CT images, the contamination seems massive but in contrast to the first run, the generated top of the plug is more stable since less contaminated cement slurry left the pipe during recovery phase. Nevertheless, the contamination is enough to create a wet plug with a too low compressive strength in order to withstand the possible impact force of a drill bit. The cement fell through the base fluid and failed in the end to generate a drillable kick-off plug. One surprise was that the induced swabbing force was high enough to drag some of the base fluid into the cement matrix. J. Heathman and Carpenter (1994) reported that swabbing induced contamination will increase if a more viscous slurry is used. A comparison of the swabbing pressure from the first simulation (7140 Pa) to the swabbing force induced during the second run (10135 Pa) confirms the assumption made by J. Heathman and Carpenter (1994). This is one reason why the observed contamination is higher than expected even if the pulling speed is reduced by 0.67 m/sec. compared to the first experimental simulation. The CT scans confirm the theory since spots of base fluid are displayed on the images (especially in Figure 61c). Surprisingly a relative homogenous cement mass is located at the middle part of the plug (Figure 61e). A visual observation of the recovered plug would not predict this cement quality but would assume a complete intermixing between the base fluid, the cement and some drilling fluid at this location.

6.2.6 Simulation 3

6.2.6.1 General

The goal of the third simulation run is to test the reliability of the software's fluid interface prediction for the case that the evaluated design parameter indicates a stable interface that is very close to the red 45° threshold line. In other words, the simulation is conducted to test the critical stability region of the plot. Compared to the prior conducted runs, the density difference between the base fluid and the slurry is reduced in a way that the software calculates a stable interface located near the threshold line between the green stable and the red instable region (Figure 63). Furthermore, a pipe pulling speed is selected that triggers a laminar flow regime for both, the cement slurry and the drilling fluid. The wellbore is deviated and shows an inclination of 35°.

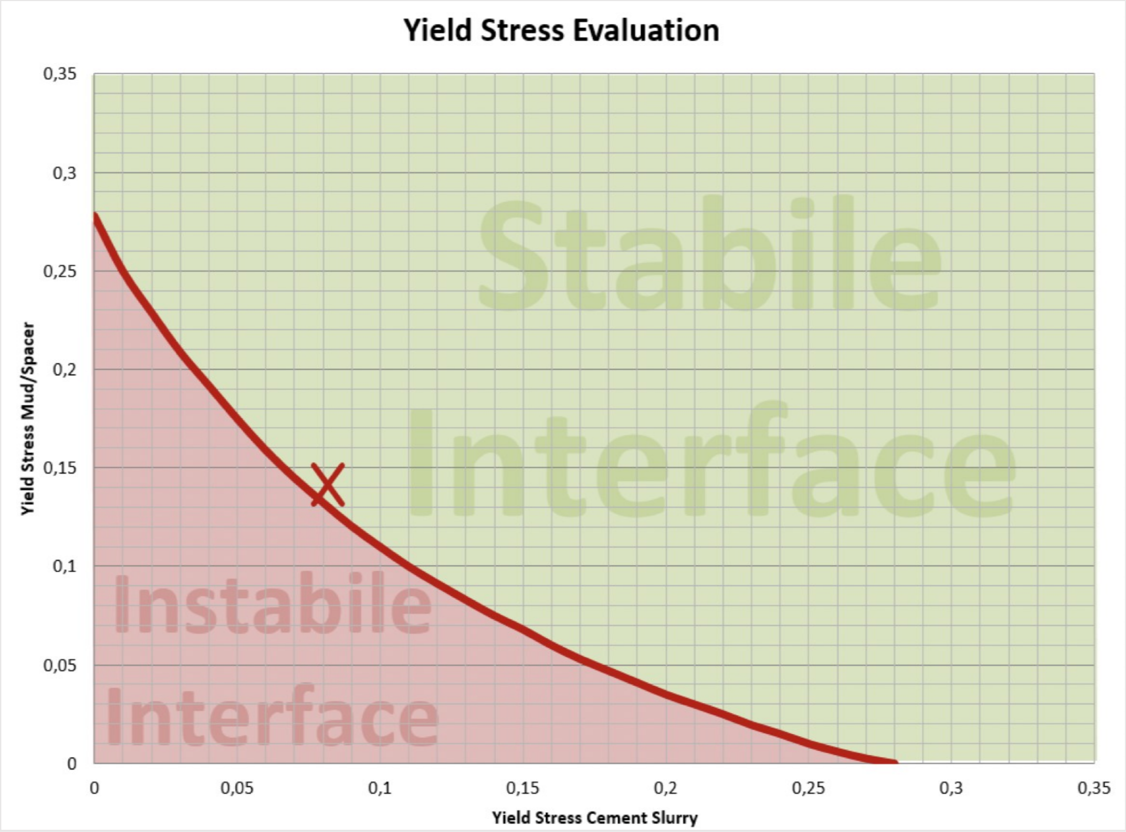


Figure 63: Interface stability plot for the third simulation (inclination 35°)
The fluid properties are chosen in a way that the software predicts a stable interface that is located near the red threshold line. The simulation tests the critical stability region of the design plot.

6.2.6.2 Fluid Parameters

The drilling mud specifics for the third simulation are listed in Table 6. The measured base fluid characteristics as well as the cement properties can be seen in Table 13 and Table 14. The density of the base fluid is increased from 1222 kg/m^3 or 10.2 ppg to 1486 kg/m^3 or 12.4 ppg. To do so, 4100 grams of barite are added to the already mixed bentonite fluid. Due to the limited amount of barite available in the laboratory, 1486 kg/m^3 (12.4 ppg) is the upper most limit for increasing the density of the base fluid, otherwise the barite consumption would be too high.

Density					
1486 kg/m³- 12.4 ppg					
Rheology					
ϑ_3	ϑ_6	ϑ_{100}	ϑ_{200}	ϑ_{300}	ϑ_{600}
42	49	61	79	95	135
10 sec. gel			**10 min. gel**		
45			55		
pH					
9.18					
Resistivity					
10.25 Ωm					

Table 13: Lab measured properties of the base fluid for the third simulation

The measured yield stress of the base fluid is 11.5 Pa or 55 lb/100 ft^2. The density of the bentonite pill is increased, using barite as a weighting additive. The measured density of the fluid is 1486 kg/m^3 or 12.4 ppg.

Density					
1558 kg/m³- 13 ppg					
Rheology					
ϑ_3	ϑ_6	ϑ_{100}	ϑ_{200}	ϑ_{300}	ϑ_{600}
39	45	51	58	70	110
10 sec. gel			**10 min. gel**		
-			-		

Table 14: Lab measured properties of the cement slurry for the third simulation

The measured density of the cement slurry is 1558 kg/m^3 or 13 ppg. The calculated yield of the cement slurry is 6.26 Pa or 30 lb/100 ft^2.

6.2.6.3 Predicted Design Parameters of the Program

For the prediction of the software, all relevant parameters described in Table 6, Table 13 and Table 14 are used. As already described, the goal of this simulation is the production of a kick-off plug that is set with critical fluid interface values. The cement plug can slump down, fall through the plug base or stay stable as predicted. Figure 63 is the resulting plot of the software, indicating one of the design parameters. All output parameters are listed in Table 15.

Slurry volume needed	
10.23 litres	
Predicted interface stability	
Stable interface but critical stability region	
Pressure drop req. to erode mud	**Pressure drop generated**
0.0035 bar	0.0052bar (@ 0.31 m^3/min pump rate)
Critical velocity cement	**Induced annular velocity**
1.82 m/sec	0.99 m/sec. (@ 0.6 m/sec. pulling speed)
Induced swab pressure	**Flow regime cement**
8729 Pa	Laminar (@ 0.6 m/sec. pulling speed)

Table 15: Software predicted design parameters for the third simulation

6.2.6.4 Laboratory Simulation

For executing the simulation, all tools and auxiliary means described in chapter 6.1 are used. During the first step, the stinger pipe is connected to the hook of the steel rope of the drawworks and lowered into the borehole. After running in hole (RIH) the prepared K_2CO_3 drilling mud is pumped via manifold and the transparent hose downhole (Figure 48a). The mud is then left for one hour under static conditions to apply gel strength and to recover from the shear forces applied during pumping operation. In the meanwhile, the pump is cleaned with fresh water and the viscous base fluid prepared for the next step. After pumping the base fluid down the well, the stinger is pulled slowly to the designated cement plug location. The simulation should assess primarily the prediction quality of the interface stability between the base fluid and the cement in case that the software calculates a design parameter located in the critical stability region of the plot. Prior simulation it is not clear if the cement slurry falls through the base, slumps down or stays stable as indicated. According to the prediction of the software a slightly stable interface should be formed (Figure 63). To test the design parameters of the program, 10 litres of 1558 kg/m^3 or 13 ppg cement slurry are pumped downhole. For the slurry, 7387 grams of mix water and 8231 grams of neat Class G cement are used (for calculating the right quantities, equation [29] is applied). After placing the cement plug on the viscous pill, the stinger is pulled with 0.6 m/sec. from the wellbore. The implemented tripping speed should induce an annular velocity of 3.26 m/sec. and therefore not exceed the critical velocity of both, the cement (5.98 m/sec.) and the drilling mud (10.33 m/sec.). According to the program, a laminar flow regime is generated in the borehole and no or only little turbulences are expected. The expected contamination should be smaller. When the drillpipe is pulled of hole, the wellbore is tilted approx. 35° in order to simulate an inclined borehole. After approx. 24 hours of curing time, the drilling mud is poured out from the pipe and the complete wellbore recovered from the cellar.

6.2.6.5 Visual Observation and Findings

During the pumping procedure of the polymer mud and the base fluid, no distinct abnormalities could be observed. The heavy bentonite pill displaced the lighter mud upwards as expected. A sharp transition between both liquids was visible. Also, no abnormalities could be monitored during cement pumping job. As soon as the wellbore was tilted, the fluid interface between the bentonite base and the cement failed. The effect was not that severe compared to the second simulation where the plug fell though the base but it could be observed that some of the heavier cement was sliding down the wellbore wall, pushing the lighter base fluid upwards (the phenomenon is also described by J.F. Heathman (1996) and can be found in chapter 4.1.3.2). Figure 64 shows the upper and Figure 65 the lower side of the borehole. The sliding process of the cement slurry was slowly and at the beginning it seemed that only a little portion of the cement slides down. After 24 hours, more cement than expected slipped down the pipe, but the upper part of the plug seemed to be uncontaminated and in full integrity. On a visual basis, the contamination of the cement slurry with drilling mud was also low. The pulling speed was small enough in order to generate a laminar flow pattern and to keep the turbulences on a minimum.

Figure 64: Top side view of the wellbore

Some of the bentonite fluid was displaced upwards by the slumping cement and mixed with the slurry. The predicted interface stability did not occur.

Figure 65: Bottom side view of the wellbore
Some of the cement slurry slumped down the wellbore wall. At the place where one can see the cement, normally the base fluid is located. The fluid was pushed upwards and replaced by the cement.

6.2.6.6 CT Interpretation

The recovered and processed kick-off plug is scanned with the CT. Figure 66 shows the plug prior scanning process. The examined sample is the tallest of all plugs. The difference between the specimen used for this scan and all other samples is the fact, that the base fluid is left in the pipe. This has practical reasons since, some of the cement slumped downhole pushing the lighter base fluid upwards. The cement allocated at the base plate of the Plexiglas pipe and cured there. A safe removal of the base fluid is not possible. Figure 67a displays the complete scanned cement plug in a 3D view and Figure 67b shows the same deviated plug from the front. The plug is cut in the middle to illustrate inhomogeneities and discrepancies.

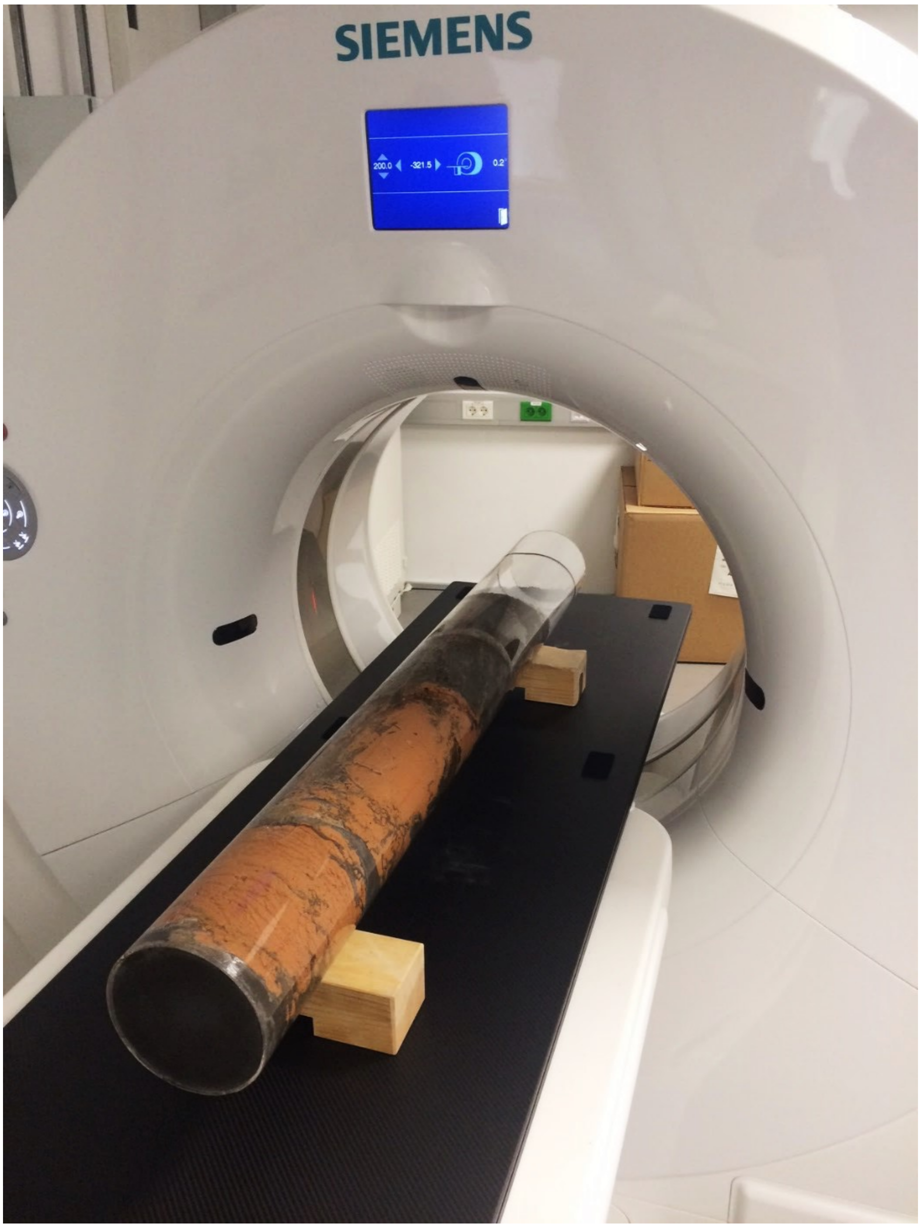


Figure 66: Cement Plug No. 3 prepared for CT scanning

The difference between the specimen shown in this picture and all other plugs is, that here the base fluid is left in the pipe (red/brown fluid), since the slumped and cured cement plugs the complete base plate and a save removal of the slurry is not possible.

The interpretation of the scans shows that the plug is partly contaminated in the upper fraction (red arrow). Compared to the previous simulations (Simulation 2) the contamination is less and there is also no formation of a structure like a funnel or chimney (Figure 60a-b). The missing funnel is interpreted as the result of the predicted laminar flow regime. The side view of the 3D plot (Figure 67a) also shows smaller contamination of the upper zone compared to the second plug (Figure 60a). Nevertheless, lesser contamination was expected in the forefront taking the predicted number as a reference value. Following the contaminated zone, a part of pure cement is observed in the scan. The homogenous fraction is small compared to the total length, but it is clearly indicated that this part is free from any inadvertent event. The lower part caused some troubles during CT scan. It seems that the base fluid has a high tendency to absorb the nuclear radiation of the scanner. Several scans with different parameters delivered always the same result. The viscous base creates a halo in the CT images and makes an interpretation nearly impossible. Only the side view (Figure 67a) allows some conclusion and shows the displaced bentonite suspension (green arrow). The grey mass at the bottom of the scan (blue arrow) is the slumped and cured cement that triggered problems during CT preparation phase. The cement blocked the cap and made a removal of the base fluid unfeasible.

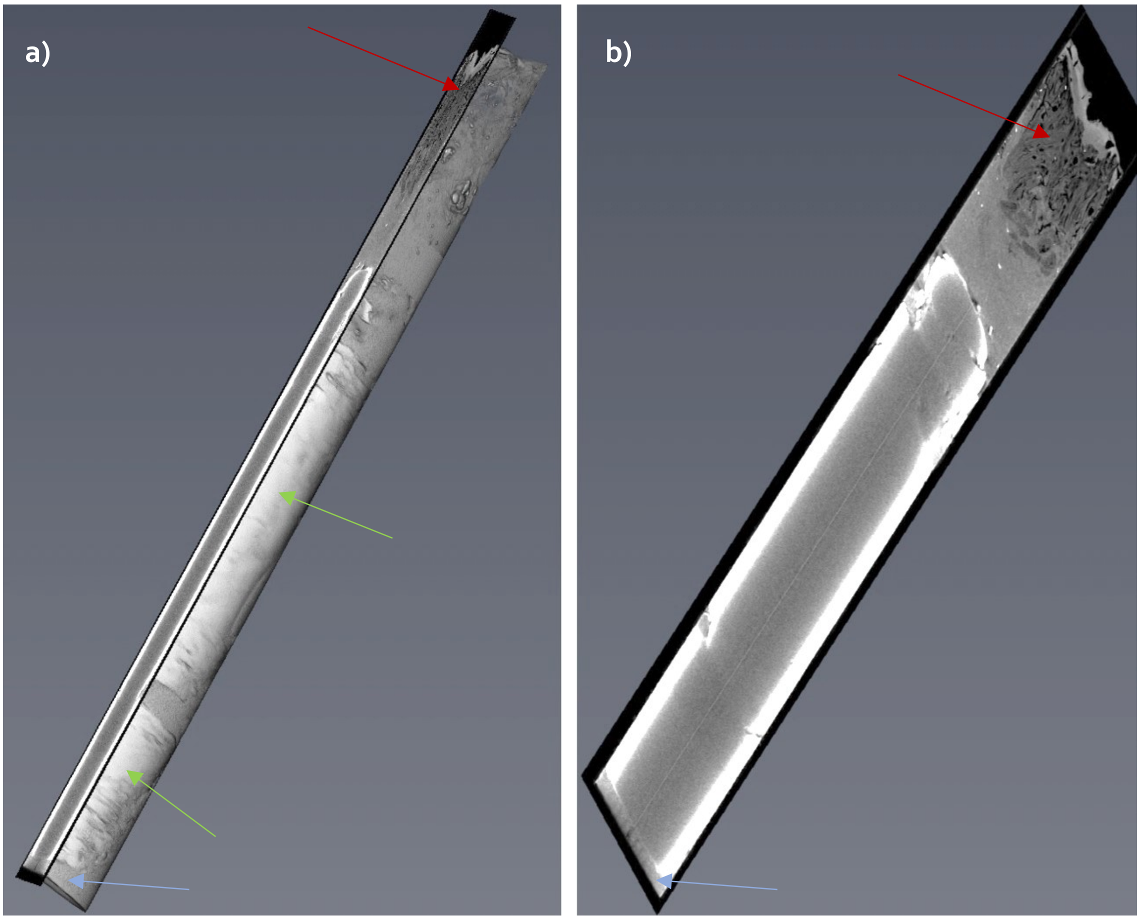


Figure 67: Scanned plug No. 3 in 3D view (left) and front view (right)

To investigate the cross-sectional quality of the third plug, four particular locations within the plug are selected. The overview of the position as well as the specific slices are shown in Figure 61a-e. The interpretation of the slices shows some contamination in the upper part of the plug (1). The intermixing between the drilling mud and the cement is less compared to the previous simulation. Less fluid (black) and more cement (grey) indicates that the laminar flow regime causes less troubles. The second slice (2) displays a fraction of pure and uncontaminated cement. The third slice (3) is a cross section of the transition zone between the pure cement and slumped part. The white halo in the middle flags the base fluid that was pushed upwards during tilting process of the wellbore. The grey ring on the outside of the cross section is cement with some impurities of bentonite suspension (red arrows). The fourth slice (4) is an image of the lower part. Due to the tendency to absorb the nuclear radiation, only base fluid is displayed in the picture.

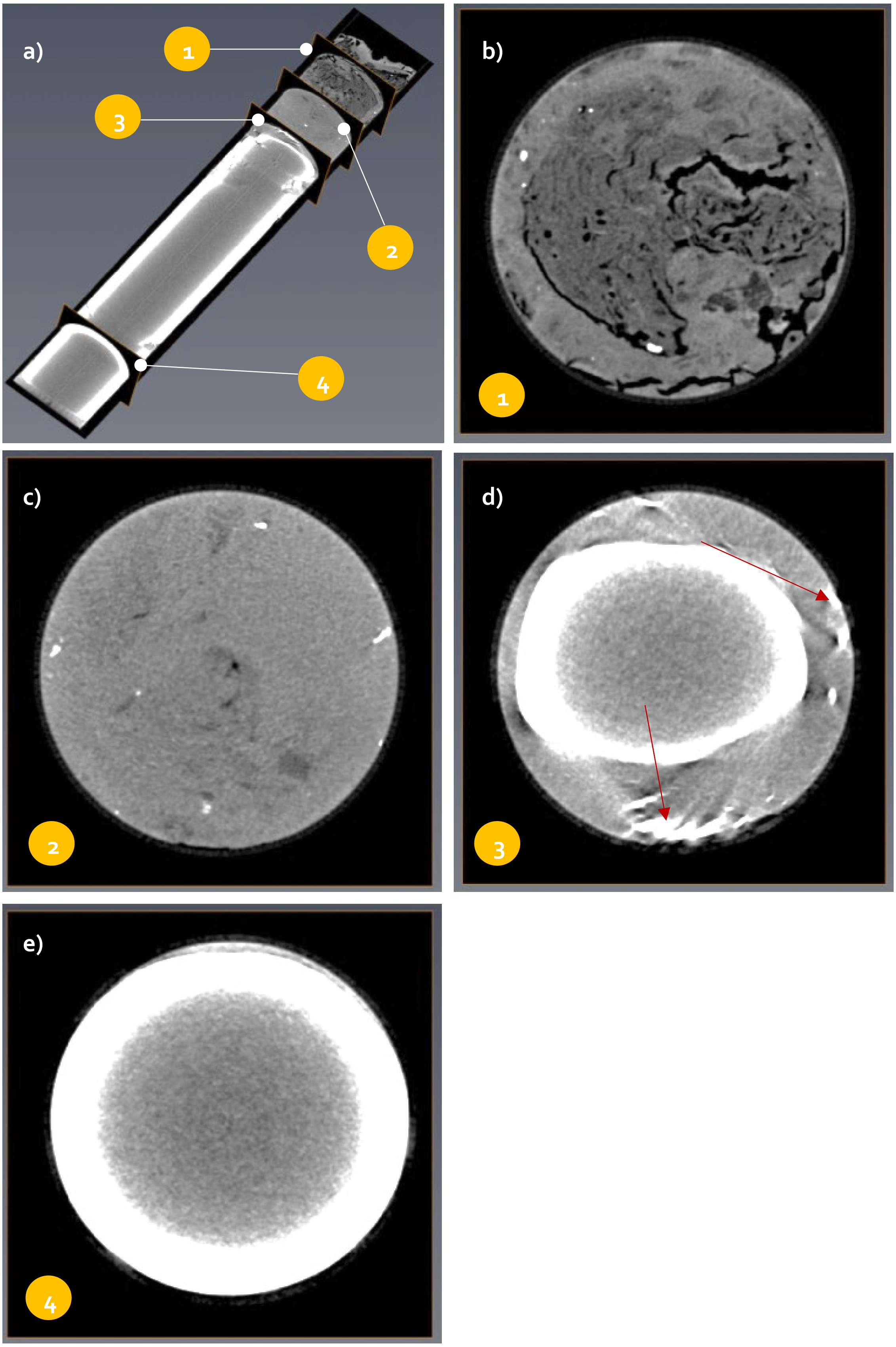


Figure 68: Cross sectional interpretation of plug 3
Four different slices (1-4) are cut from the scanned plug. Slice (1), (2) and (3) are displaying the top section and slice (4) the lower part of the plug.

6.2.6.7 Comparison of Software and Simulation Results

The laboratory simulation was conducted with the same parameters which were used for the software prediction. The results of the software are listed in 6.2.6.3. Figure 63 shows the predicted inclined interface stability plot generated by the software. The red cross is located at the border line between a stable and an instable interface. According to the software, a slightly stable interface should appear. In the laboratory simulation, the interface between the base fluid and the cement slurry failed, but the overall quantity of slurry that slipped down the wellbore was small, compared to the rest of the plug volume. The slumped cement is also indicated in the CT scans. The plug is divided into a smaller contaminated part on top, followed by a pure cement fraction and the slumped area. Because of the tendency of the base fluid to absorb the nuclear radiation no investigation is conducted in the lower part of the plug, but it seems that the smaller portion of cement slumped down the wellbore wall. Nevertheless, the plug failed and it can be stated that if the software predicts a design parameter located at the critical interface stability region, the basic input variables should be changed in order to generate a more stable fluid interface.

6.2.6.8 Conclusion

The evaluated design parameters of the software and the observed outcomes of the simulation run did not fit in all points. The predicted flow regime concurred with the monitored slurry contamination. Compared to the previous runs, a laminar flow regime keeps the mud contamination of the cement plug on a low level, but it was expected that the predicted flow regime has less influence on the contamination. The CT images show more contamination than a visual observation would assess but compared to the previous simulation where the intermixing is massive, the contamination in this plug is kept within a limit. A reason for the cement contamination is probably the application of an open-ended stinger rather than a diverter tool. As soon as the stinger leaves the plug during pulling operation, some of the residual cement might fall out of the pipe and intermixes with the drilling fluid. In case of a diverter tool, much less cement escapes from the pipe and there might be fewer complications regarding contamination of the upper fraction of the kick-off plug. The interface stability shows differences between prediction and actual experimental outcome. The simulation assumed a slightly stable interface whereas the cement plug in the laboratory slumped partly through the viscous plug base. In case that the software predicts a design parameter as seen in Figure 63, one recommendation is to increase the basic input variables such as yield point of the fluids with respect to a more stable interface. Another option is to decrease the density difference according to the suggestion of J. Heathman and Carpenter (1994). They recommend, that the difference between the base fluid and the cement slurry should be kept within 0,2 to 0,5 lb/gal (24 kg/m^3 to 60 kg/m^3). It also must be stated that the prediction might be true in case that a diverter tool is used instead of an open ended drillpipe as it was the case in the simulation. The open-ended stinger simulates the worst-case scenario where the cement directly falls on the base fluid, whereas the diverter tool disarms some of the circumstances that trigger the slumping tendency of the slurry.

6.2.7 Simulation 4

6.2.7.1 General

The aim of the fourth and last simulation run is the production of a perfect cement plug. To do so, basic input variables are chosen in a way that the density difference between the base fluid and the cement slurry is within the recommended threshold in order to create a stable interface. Furthermore, the yield of the bentonite suspension as well as the cement slurry is manipulated with respect to fluid interface stability. The high yield of both liquids increases the chance for a successful cement plug. Figure 69 shows the predicted interface stability plot of the software. According to the program, the assessed interface between both fluids should be very stable. Another improvement is the simulation of a sacrificial stinger in order to minimize contamination effects between the slurry and the drilling fluid. If a sacrificial stinger is used, the pipe pulling speed is set to zero and the drillpipe is left in the hole. The experimental run is conducted to evaluate the effect of a sacrificial tubing as well as the influence of a thick cement and base fluid with respect to a successful kick-off plug. The wellbore is deviated and shows an inclination of 26°.

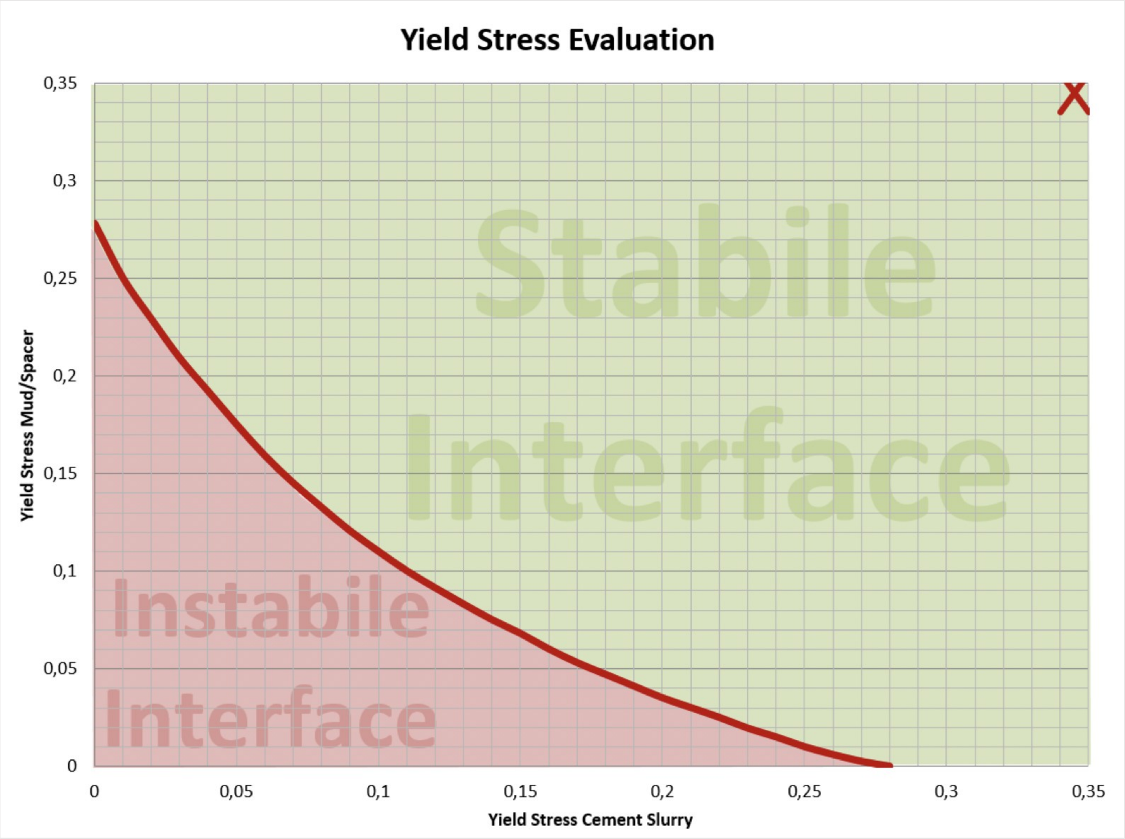


Figure 69: Interface stability plot for the forth simulation (inclination 26°)
The red cross is located in the upper right corner of the plot indicating a stabile interface between the cement slurry and the base fluid

6.2.7.2 Fluid Parameters

The drilling mud specifics for the fourth simulation are listed in Table 6. The evaluated base fluid characteristics as well as the cement slurry properties are listed in Table 16 and Table 17. The density of the base fluid is set to 1582 kg/m^3 or 13.2 ppg. To do so

5766 grams of barite are added to the bentonite suspension. To increase the viscosity and the yield of the base fluid, a high temperature resistant starch is added to the fluid. The density of the cement slurry is set to 1618 kg/m^3 13.5 ppg. The difference between both fluids is very small and therefore within the recommended threshold value of 24 kg/m^3 to 60 kg/m^3 or 0.2 to 0.5 ppg. The viscosity as well as the yield of the cement slurry are also increased in order to support a stable fluid interface. To do so, 2.5 wt% of a high temperature resistant starch is added to the slurry.

<table>
<tr><th colspan="6">Density</th></tr>
<tr><td colspan="6">1582 kg/m^3- 13.2 ppg</td></tr>
<tr><th colspan="6">Rheology</th></tr>
<tr><td>ϑ_3</td><td>ϑ_6</td><td>ϑ_{100}</td><td>ϑ_{200}</td><td>ϑ_{300}</td><td>ϑ_{600}</td></tr>
<tr><td>70</td><td>85</td><td>132</td><td>165</td><td>215</td><td>270</td></tr>
<tr><th colspan="3">10 sec. gel</th><th colspan="3">10 min. gel</th></tr>
<tr><td colspan="3">76</td><td colspan="3">200</td></tr>
<tr><th colspan="6">pH</th></tr>
<tr><td colspan="6">9.25</td></tr>
<tr><th colspan="6">Resistivity</th></tr>
<tr><td colspan="6">10.32 Ωm</td></tr>
</table>

Table 16: Lab measured properties of the base fluid for the fourth simulation

The measured yield of the base fluid is 33.4 Pa or 160 lb/100 ft^2. The yield of this base fluid is the highest of all compared to the other simulations. The measured density of the fluid is 1582 kg/m^3 or 13.2 ppg.

<table>
<tr><th colspan="6">Density</th></tr>
<tr><td colspan="6">1618 kg/m^3- 13.5 ppg</td></tr>
<tr><th colspan="6">Rheology</th></tr>
<tr><td>ϑ_3</td><td>ϑ_6</td><td>ϑ_{100}</td><td>ϑ_{200}</td><td>ϑ_{300}</td><td>ϑ_{600}</td></tr>
<tr><td>52</td><td>68</td><td>84</td><td>106</td><td>152</td><td>192</td></tr>
<tr><th colspan="3">10 sec. gel</th><th colspan="3">10 min. gel</th></tr>
<tr><td colspan="3">-</td><td colspan="3">-</td></tr>
</table>

Table 17: Lab measured properties of the cement slurry for the fourth simulation

The yield of the cement slurry is also increased in order to prohibit slumping effects of the slurry. The measured yield is 23.4 Pa or 112 lb/100 ft^2.

6.2.7.3 Predicted Design Parameters of the Program

As already described in the previous section, the goal of this simulation is the production of a perfect cement plug that is set successfully on the first attempt in order to sidetrack the wellbore without any troubles. For the design parameter evaluation, input variables from Table 6 as well as Table 16 and Table 17 are used. The stinger tube that is used to pump down all the fluids is designed as a sacrificial drillpipe that is left in the borehole after cementing the plug. Therefore, the critical and induced annular velocities as well as the swab pressures are set to zero. Table 18 shows the results of the software prediction.

Slurry volume needed	
10.23 litres	
Predicted interface stability	
Stable interface	
Pressure drop req. to erode mud	**Pressure drop generated**
0.0035 bar	0.0052bar (@ 0.31 m³/min pump rate)
Critical velocity cement	**Induced annular velocity**
0 m/sec	0 m/sec. (sacrificial tubing)
Induced swab pressure	**Flow regime cement**
0 Pa	No flow (sacrificial tubing)

Table 18: Software predicted design parameters for the fourth simulation

6.2.7.4 Laboratory Simulation

For executing the simulation, all tools and auxiliary means described in chapter 6.1 are used for this run. During the first step, the stinger pipe is lowered into the wellbore. After running in hole (RIH) the prepared and sheared drilling mud is pumped via manifold and the transparent hose into the well (Figure 48a). Prior pumping the base fluid, the potassium mud is left for one hour static in the borehole in order to recover from the pumping and shearing action. In the meanwhile, the pump is flushed with water. Before the base fluid can be pumped into the wellbore, the viscosity must be increased. To do so, a high temperature resistant starch is used. The starch is mixed to the already prepared and weighted bentonite suspension. After increasing the viscosity, rheological measurements are conducted in order to adapt to the values of the input variables from the software program. In a next step, the base fluid is placed in the wellbore and the stinger raised to the designated cement plug location. Prior pumping the cement slurry into the wellbore, also the viscosity of the slurry is increased. Therefore, 2.5 wt% of a high temperature resistant starch is weighed and added to 10 litres of slurry. The starch immediately reacts with the cement and improves the rheological behavior. For preparing the slurry, 7108 grams of mix water and 9109 grams of neat Class G cement are used (for calculating the right quantities, equation [29] is applied). According to the prediction of the software the enhanced fluids should create a stable interface. After balancing the plug on the viscous bentonite mud, the stinger is left in the borehole. If this is the case the drillpipe is called sacrificial. On the field, the sacrificial tubing is disconnected from the rest of the drillstring and left in the wellbore. In order to preserve the drill bit, the sacrificial tubing is manufactured of aluminum steel. The basic principle of a drillable pipe is described in chapter 2.4.5. After disconnecting the Plexiglas stinger pipe in the laboratory from the transparent hose and swivel, the complete wellbore is tilted to 26° (Figure 70). In a last step, all surface equipment is cleaned, preserved and stored for next laboratory use.

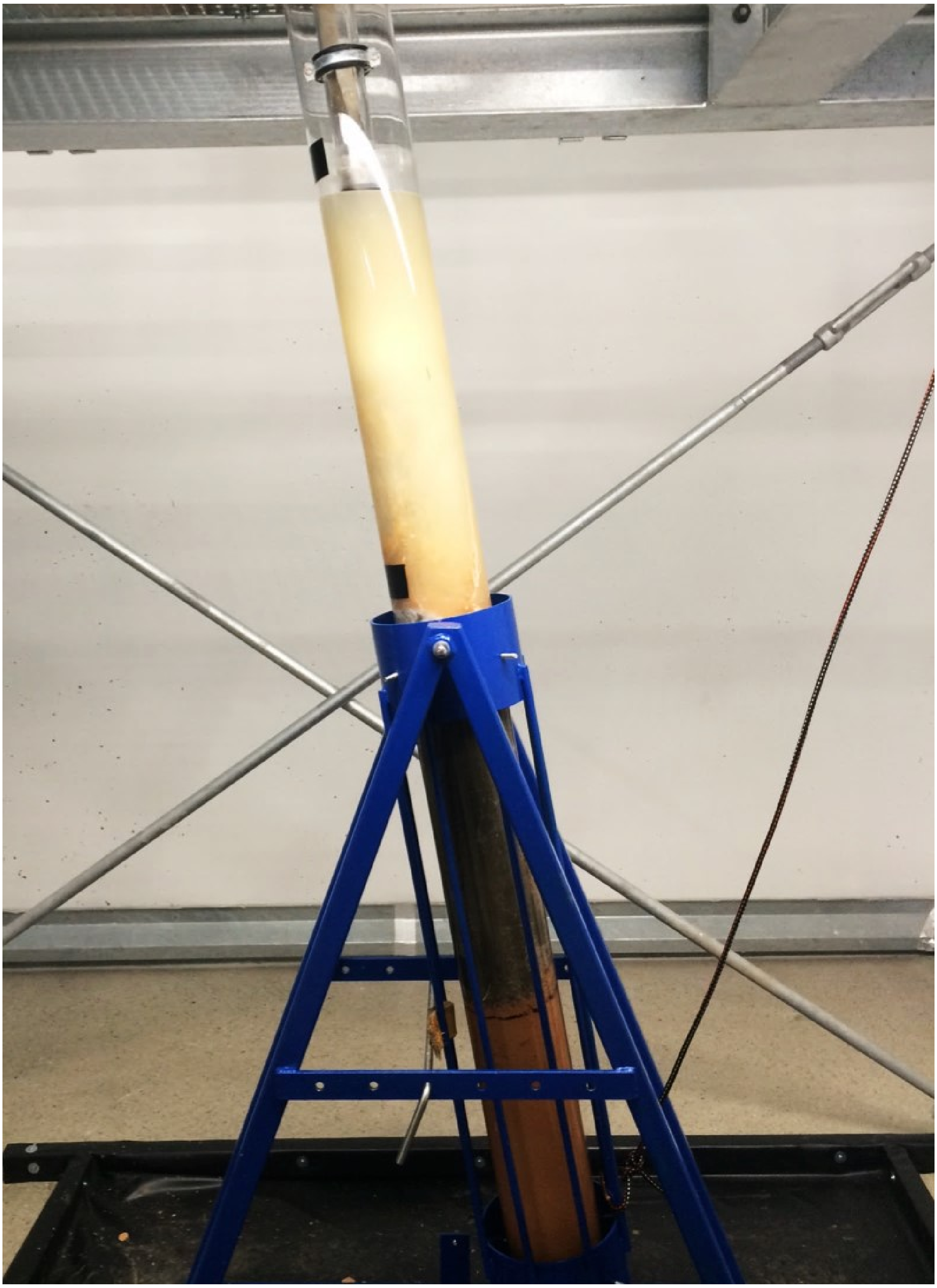


Figure 70: Cement plug No. 4 set in an inclined wellbore
The stinger is left in the wellbore after cementing operation. This procedure is called sacrificial drillpipe and should procure no turbulences or contamination.

6.2.7.5 Visual Observation and Findings

During the pumping procedure of the polymer mud and the base fluid, no abnormalities could be observed. The heavy and viscous bentonite pill displaced the K_2CO_3 mud upwards as expected. A sharp transition between both liquids was visible. The pumping of both fluids never caused troubles in any simulation run. Even when the viscosity of the bentonite suspension was raised as described in 6.2.7.2, no irregularities were monitored. Also, no abnormalities could be monitored during cement pumping job. The low density difference and the high viscosity and yield of both liquids formed a stable interface. Compared to the third simulation where the cement slipped down on the lower side of the wellbore wall, the interface between the slurry and the base fluid was stable. After disconnecting the stinger pipe from the hose and swivel, the wellbore was tilted. An immediate observation of the plug base showed that the cement stayed in place and did not move when the borehole was inclined, in contrast to the slurry behavior and findings described in the third run. The stinger pipe was implemented as a sacrificial tubing and left in the borehole after cementing (Figure 70). Therefore, no swabbing induced contamination between the cement and the drilling fluid was observed. Nevertheless, some small dynamically induced turbulences between the cement and the drilling fluid were monitored. The turbulences might be a consequence of the direct impact force of the pumped slurry on the drilling mud and base fluid during the initial phase of the cementing operation and the overall stinger design as an open-ended drillpipe rather than a diverter tool.

6.2.7.6 CT Interpretation

Figure 71 shows the fourth plug prepared for the CT scanning operation in the lab.

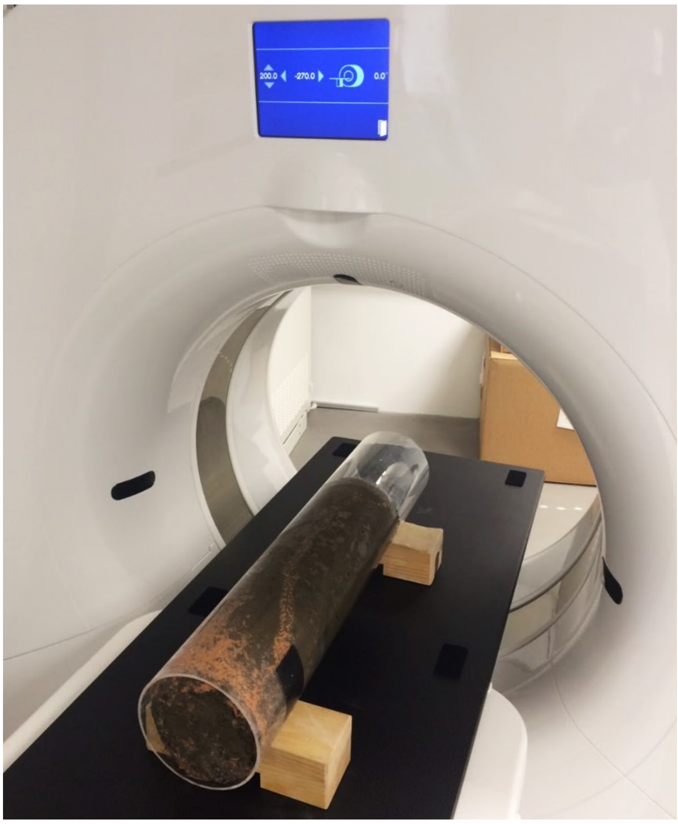


Figure 71: Cement Plug No. 4 prepared for CT scanning

The cement plug is investigated with the CT after recovery process. In contrast to the last simulation (Simulation 3) all fluids are removed from the wellbore. This should guarantee a successful scanning procedure without any interference. Figure 72 displays the complete scanned cement plug in a 3D view and Figure 73 shows the same deviated plug from the front. The plug is cut in the middle to illustrate inhomogeneities and discrepancies.

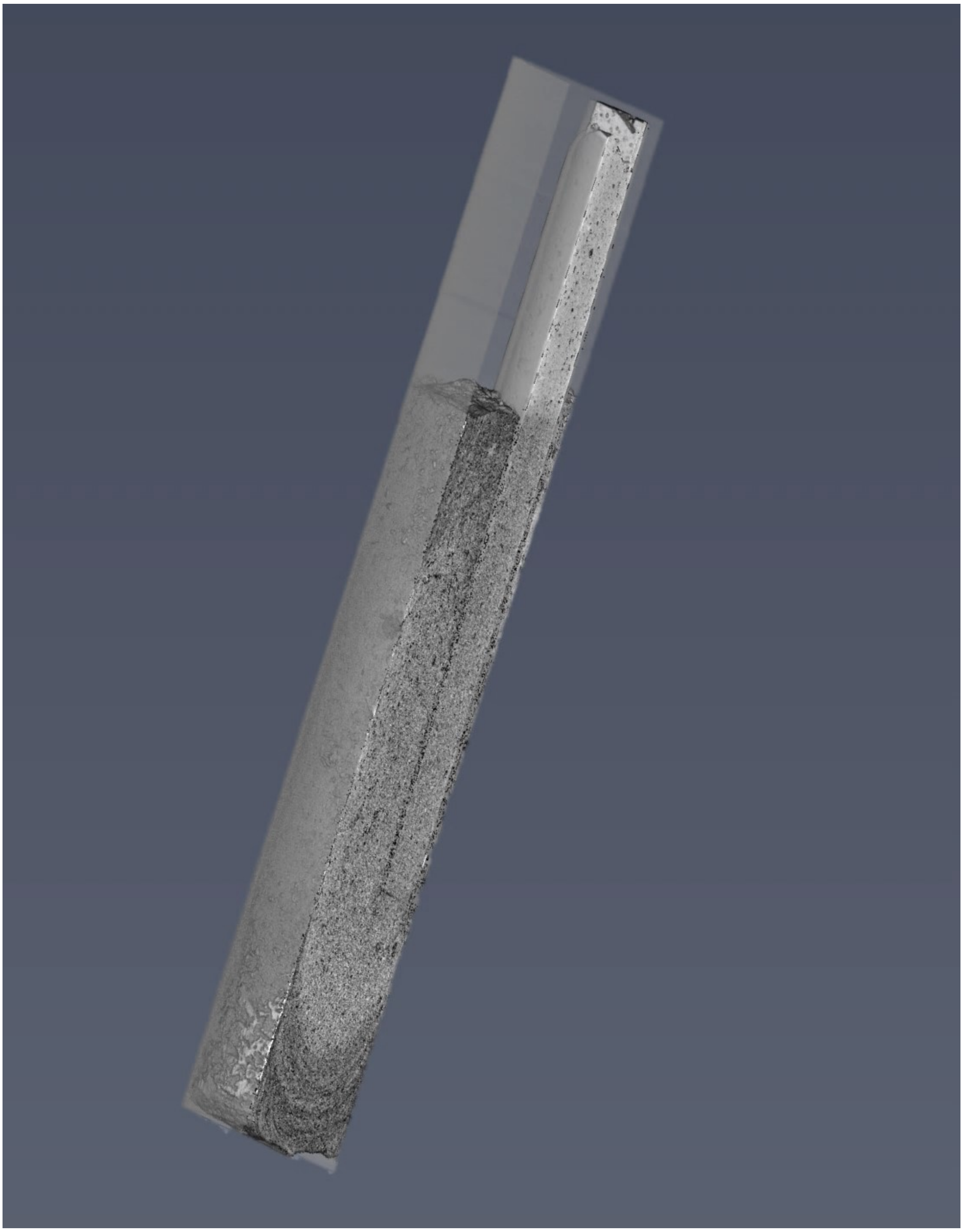


Figure 72: Scanned plug No. 4 in 3D view
The image shows the scanned plug from the last simulation run in a 3D view. The outer light grey structure is the Plexiglas tube from the wellbore and the stinger pipe respectively. The picture clearly indicates the cement plug with the sacrificed drillpipe.

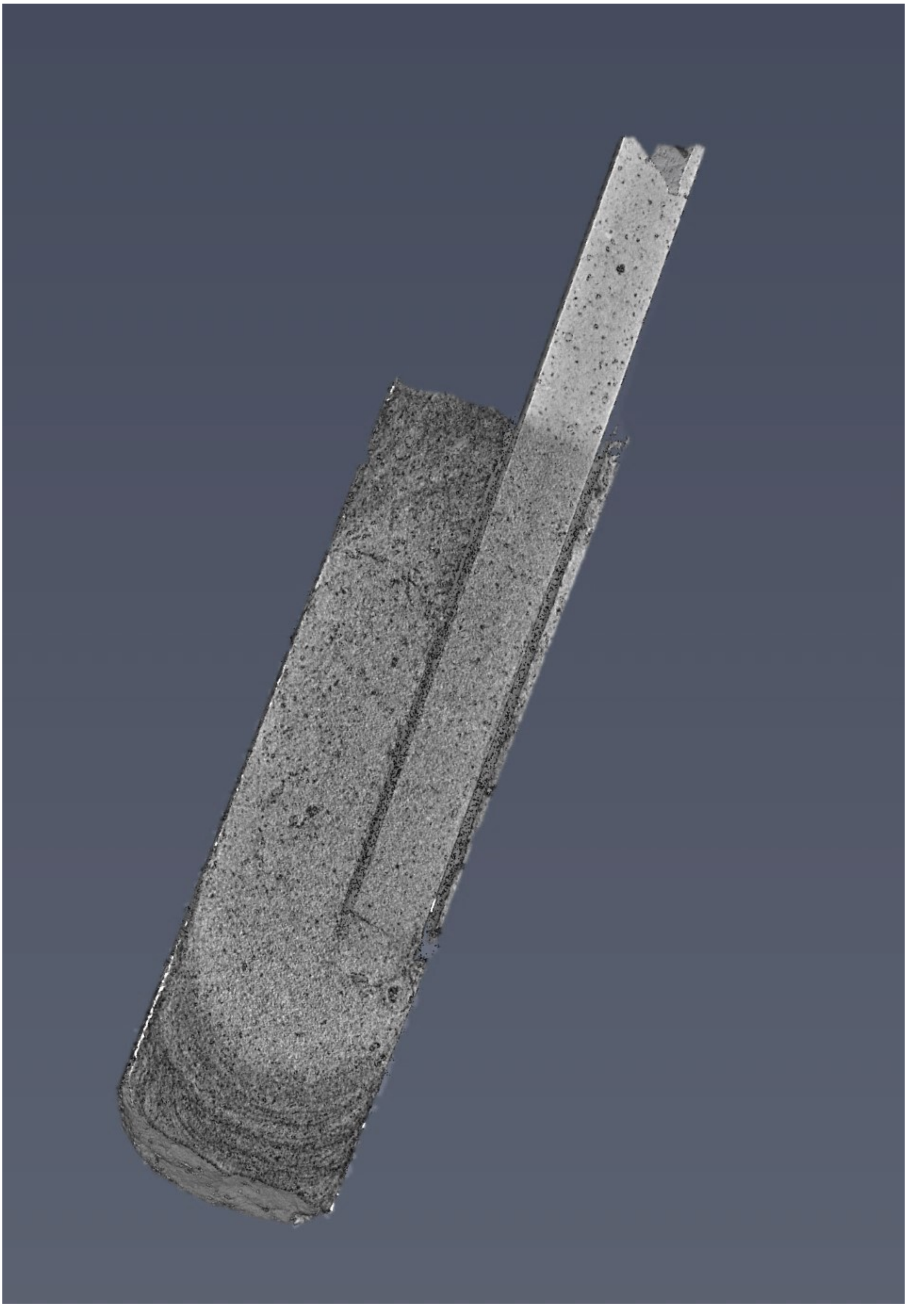


Figure 73: Scanned plug No. 4 in a front view
The image shows the scan of the plug in a front view. The actual plug as well as the cement filled stinger pipe (sacrificial) is clearly displayed in the picture.

In the overview, the CT scan shows a nearly perfect cement plug. No contamination is visible in the upper part of the plug. This is because the pipe was not pulled after the cementing operation but left in the hole in order to avoid turbulences and intermixing of the slurry and the drilling fluid. It could be proven that a sacrificial drillpipe minimizes the risk of cement contamination on a high level. The calculated volume used for the plug is based on an over-displaced slurry design. This means that the slurry level in the stinger must always be higher than the cement level in the annulus in order to compensate the volume of the drillpipe steel when pulling the tube. The design was not changed for this simulation to prove the volume calculation of the program. The cement filled stinger shows that the pipe is over-displaced and the calculated slurry volume of the software correct. Furthermore, a very sharp plug base is observed. This observation verifies the predicted stable fluid interface and therefore the outcome of the program. To investigate the cross-sectional quality of the fourth plug, three particular locations within the plug are selected. The overview of the position as well as the specific slices are shown in Figure 74a-d.

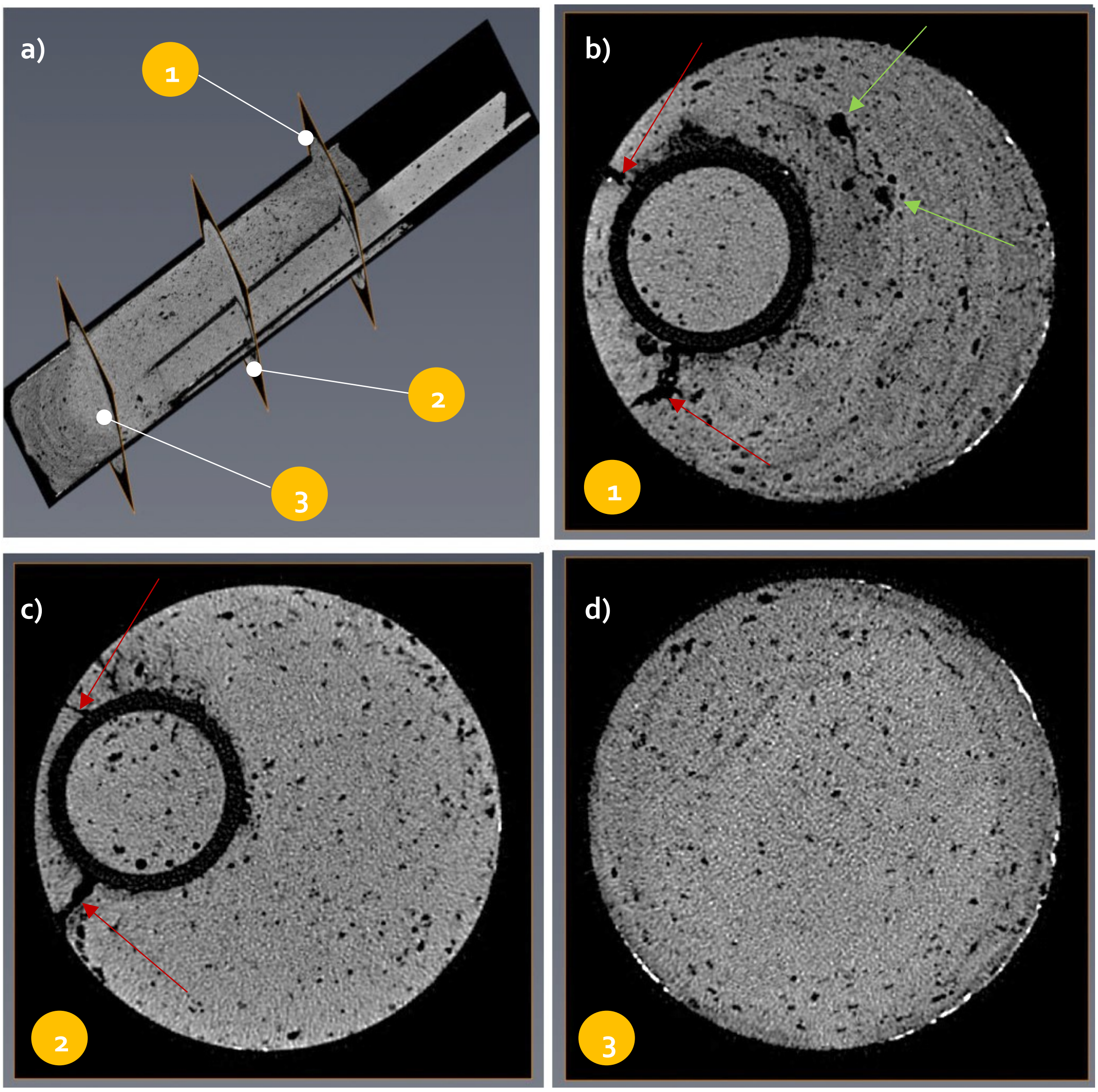


Figure 74: Cross sectional interpretation of plug 4

The interpretation of the scanned images shows a nearly perfect cement plug. In Figure 74b and Figure 74c the decentralized position of the stinger pipe is illustrated. Due to the decentralization, the cement slurry at the borehole wall is less compacted compared to the rest of the plug. This allowed some drilling fluid to form a small channel that propagates from the drillpipe to the borehole (red arrow). This is the only appreciable inhomogeneity that is found by the CT scan. In the upper part of the plug (Figure 74b) small spots of drilling mud are indicated (green arrow). Compared to the previous plugs, this cannot be mentioned as a contamination. To summarize the CT image interpretation, it can be stated that the kick-off plug produced during the fourth simulation run is classified as a successful job.

6.2.7.7 Comparison of Software and Simulation Results

Due to the optimized input variables, the software predicted a stable interface between the cement and the base fluid (Figure 69). During cementing job, a stable interface was monitored. The slightly heavier slurry floated on the lighter but more viscous base fluid. The very stable interface is also confirmed by the CT scans (Figure 72 and Figure 73). The prediction of the software is very accurate. Due to the simulation of a sacrificial drillpipe, the stinger was left in the borehole. The pulling speed as an input variable for the software was set to zero and therefore no critical and annular velocities as well as no swabbing pressure was calculated. During the simulation run, some detached clouds of cement and mud was observed. The induced small turbulences might be a result from the flowing action of the cement trough the stinger when the slurry left the lower side of the drillpipe. Because of the fact that the stinger is an open-ended pipe rather than a diverter, the impact force of the pumped slurry on the different fluids may induced some small turbulences that did not contribute to contamination. Therefore, the prediction of the software is accurate and correct. Also, no appreciable contamination can be found on the CT images.

6.2.7.8 Conclusion

Balancing a kick-off plug with a sacrificial stinger tube is one of the best options in order to generate a successful base for sidetracking a wellbore. Due to the fact that the drillable pipe is left in the wellbore, no tripping induced turbulences are generated. Zero pulling speed will cause no contamination between the cement and the drilling fluid. Therefore, it can be expected that the top of the plug is able to apply the compressive strength that is required to guide the drill bit into the right direction. A high yield and an increased viscosity of both, the base fluid and the cement mud contribute to the success of the cementing operation. The thick behaviour of the fluids attenuates or prevents the cement from falling through the bentonite base because the additional force induces a delay or resistance to flow. The produced cement plug can be stated as a perfect kick-off base since all requirements for a successful plug were matched.

6.3 Compressive Strength Experiments

6.3.1 General

The compressive strength generated by the cured cement is one of the most important parameters of a kick-off plug. If swabbing induced turbulences cause a wet plug one will not be able to sidetrack the wellbore at the designated depth. Beside a proper design phase and an accurate plug job execution, the selection of the right materials and additives influence a successful kick-off plug on a high level. Many advanced materials such as resins or other additives contribute to a higher compressive strength behaviour of the plug. The disadvantage of such materials is often a limited field of operation. Temperature effects, pumping time, shear forces, cleaning effort, high costs or availability influence the field of application. Therefore, the research for novel strength enhancing material is always a challenging but exciting duty.

A compressive strength prediction of cement slurries is nearly impossible, especially if circumstances are unstable or highly variable as it is the case in a wellbore. Every borehole has a different kind of environment and even in a well circumstance can change within one or two meters. As a result, the developed software described in Chapter 5 disclaims the compressive strength prediction as a design parameter, although there are some mathematical equations available that try to indicate the strength of a cement after a specific period of time. These equations were developed from concrete behaviour used in the construction business. Under surface conditions the cement behaves totally different compared to wellbore circumstances. Therefore, the predicted compressive strength of oil well cement, using the developed equations, might be totally off from the real applied strength in the well. The equations neglect temperature, pressure and many other effects which influence the compressive strength development on a high level. As a result, the author of this thesis was searching for novel additives that influence the compressive strength behaviour of the cement which also can be used under wellbore conditions rather than calculating approximated strength values. In the following a novel material is described in more detail that affects the compressive performance of the cement.

6.3.2 Novel strengthening additive

During the research, the author of this thesis came across a novel fiber additive. According to the manufacturer the material is composed out of strong, stiff and light fibers obtained from the extraction of nanocellulose particles of root vegetables such as carrots, or sugar beet pulps (Figure 75). The fibers are used for paints and coatings, cosmetics and concrete as a reinforcing additive but also for drilling fluids as a rheological additive. In order to disperse the novel particles, conventional industry mixing equipment can be used. One big advantage of the novel strengthening additive is the availability of raw material, the environmentally friendly behaviour and the simple utilization. Furthermore, the costs are very low compared to e.g. conventional industrial available resins.

The goal of the subsequent described experiments is to compare the compressive strength development of a conventional Class G slurry with a cement slurry where the new material is used as an additive. In the following, the experiments and their outcome are described in more detail.

Figure 75: Additive in original box
The picture shows the additive as it is delivered from the manufacturer. The ballpoint pen is used for size comparison.

6.3.3 Experiments

All experiments are conducted according to the API-10 B standard. Each slurry batch is mixed with a Chandler Constant Speed Mixer, Model 3260 and cured in a single cement cube mold. The mixer has several features including a program that automatically starts the time/ RPM configuration required in order to test after the API-10 B standard. The molds have a size of 50 x 50 mm (2" x 2") and are composed out of two side wall elements and a base plate. The side wall elements are connected via two screws located on the edge of each element, whereas a notch in the walls holds the base plate in position. Each specimen set-up consists out of a neat Class G cube and reinforced cubes. The basic ingredients are the same for all specimens. The curing time between the different set-ups varies between 24 hours to four days. All tested specimens have a density of 1753 kg/m^3 or 14.6 ppg.

In a first step, all basic ingredients for the neat Class G cube are weighed. The neat Class G cement is the same that is used for the kick-off plug experiments described in chapter 6.2. After weighing of all ingredients, the slurry is mixed with the Constant Speed Mixer according to API standards. To do so, the mixer is operated for 15 seconds at 4,500 rpm (this is the time window required in order to add the dry cement to the water in the mixer) and afterwards for 35 seconds at 12,000 RPM (this is the time window required to create a homogenous cement slurry). After mixing process, the cement slurry is poured into the prepared molds. According to the API standard, entrapped air bubbles must be released from the slurry. Therefore, a pointed screwdriver is lowered into and raised out of the slurry for several times. Furthermore, the mold is vibrated by hand to facilitate the release of the air (this procedure is conducted for every specimen). If a specimen is reinforced with the novel fibers, a designated amount of the additive is weighed (Figure 76a) and added to the mix water. In a next step the mix water is sheared together with the fibers at 10,000 RPM until all root particles are grinded (Figure 76b). Then the dry cement is added according to the API 10-B procedure.

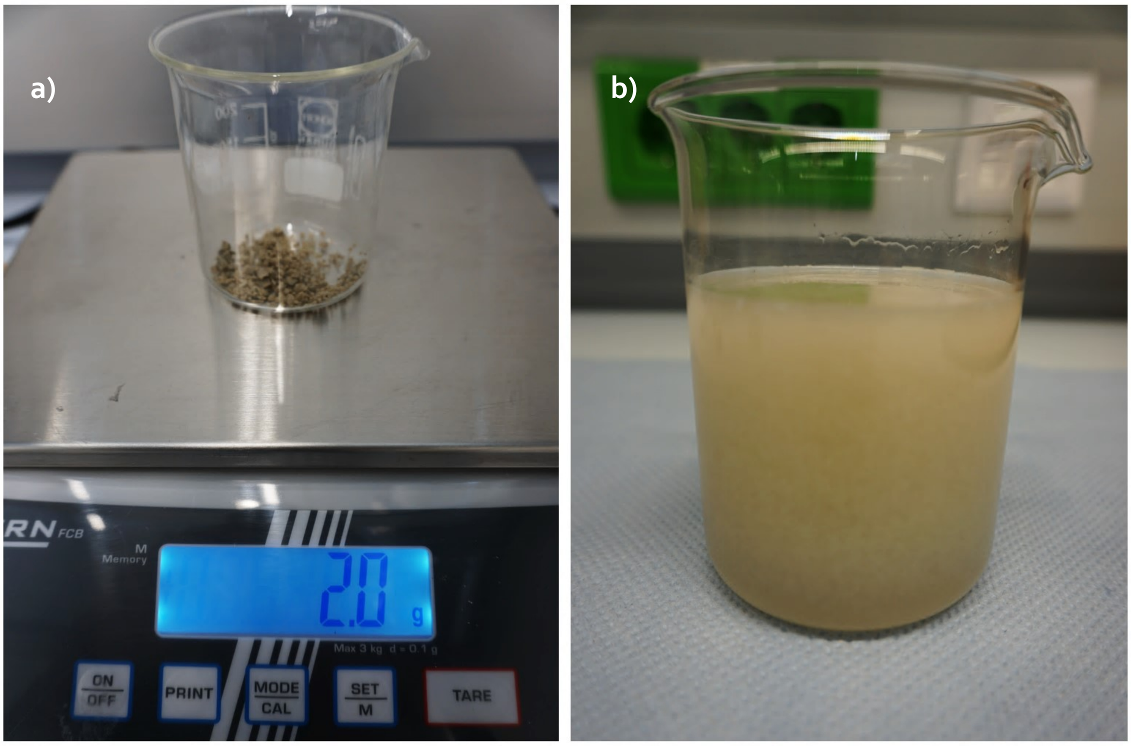


Figure 76: Weighing of the additive (right) and mixed additive (left)

During experimental research it turned out that an additive content of 3% per weight percent of cement is already too high in order to mix the slurry. Adding 3% per weight percent of cement causes the slurry to gel within seconds even during mixing process. The blenders are not able to shear the cement anymore because of the thick mass. As a result, the maximum fibre concentration is set to 2% per weight percent of cement in order to create a homogenous and pourable slurry. Table 19 shows the different number of specimens and their composition. In total 15 different samples are produced and tested.

Specimen No.	Cement Type	% of Additive	Density [kg/m^3 or ppg]	Curing Time [hours]
1	Neat Class G (Black Label)	0	1753 / 14.6	24
2	Neat Class G (Black Label)	0	1754 / 14.6	48
3	Neat Class G (Black Label)	0	1755 / 14.6	96
4	Neat Class G (Black Label)	0.5	1756 / 14.6	24
5	Neat Class G (Black Label)	0.5	1757 / 14.6	48
6	Neat Class G (Black Label)	0.5	1758 / 14.6	96
7	Neat Class G (Black Label)	1.0	1759 / 14.6	24
8	Neat Class G (Black Label)	1.0	1760 / 14.6	48
9	Neat Class G (Black Label)	1.0	1761 / 14.6	96
10	Neat Class G (Black Label)	1.5	1762 / 14.6	24
11	Neat Class G (Black Label)	1.5	1763 / 14.6	48
12	Neat Class G (Black Label)	1.5	1764 / 14.6	96
13	Neat Class G (Black Label)	2.0	1765 / 14.6	24
14	Neat Class G (Black Label)	2.0	1766 / 14.6	48
15	Neat Class G (Black Label)	2.0	1767 / 14.6	96

Table 19: Specimen composition and specifics

To test the compressive strength of the cubes, a so-called Carver Press is used (Figure 77). The press is operated by hand and uses a hydraulic fluid in order to push the piston upwards. Prior evaluating the compressive strength, the top and bottom side of the cubes are treated with sandpaper. The reason of this procedure is to establish an absolute plain surface to avoid irregularities in the height of the specimens that might influence the result of the measurement negatively. After surface treatment, the specimen is placed on the lower element (the piston element) of the press. A cross on the element indicates the position of the edges of the cube. To measure the compressive strength of the cube, the piston element is raised. To do so, the lever on the right side of the machine is moved up and down by hand. The movement pumps a hydraulic fluid into the piston and moves the lower element upwards. As soon as the cube touches the upper element of the press (the upper element is in a fixed position and cannot be moved) a noticeable resistance is monitored. It needs more force in order to press the cube against the upper element. The harder the cement, the more force is needed. The lever is moved until the specimen breaks under the applied load. A gauge on the left side of the machine measures the applied force. The maximum applied load is indicated by a red needle in the gauge. The red needle is pushed upwards by the second, black needle. In contrast to the black needle that automatically drops back to the zero position if one does not move the lever, the red needle stays at the applied maximum load. If another movement of the lever triggers a higher force, the red needle is pushed automatically by the black one to the new higher value. This allows the operator to read and note the highest applied load carefully (maximum compressive force of the cement cube) after the test is finished and the specimen crushed. To lower the piston, one must turn a wheel on the base element. The wheel opens a port to the reservoir where the hydraulic fluid is pushed back into.

Figure 77: Carver Press

6.3.4 Results

The procedure described in 6.3.3 is done for every single specimen. Figure 78 shows a graph of the force applied in the press, in order to exceed the compressive strength of the different cement cubes.

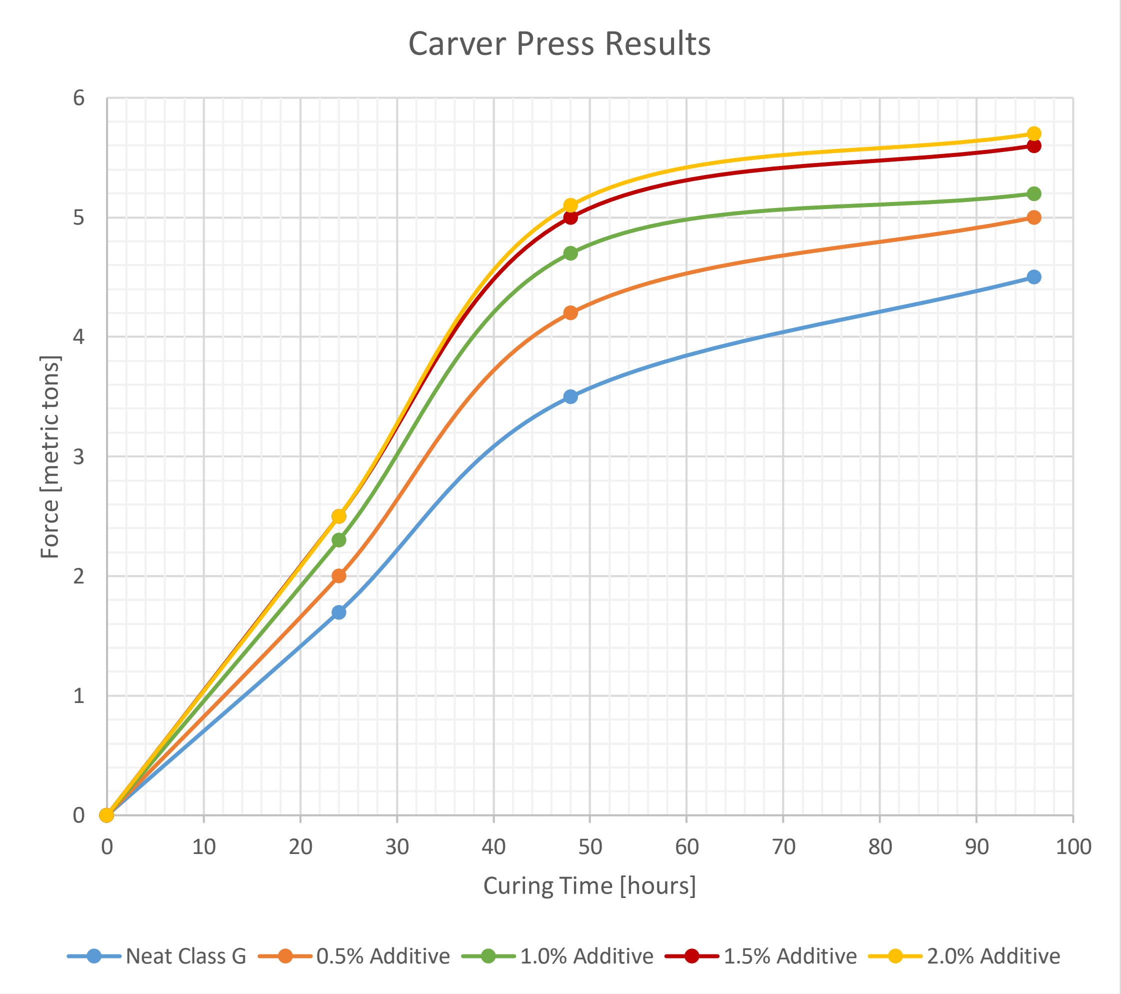


Figure 78: Carver Press results for the different samples

It is clearly indicated that the additive improves the compressive strength behaviour of the cement. Best results could be achieved with 1.5% of material added to the slurry. Adding 2% showed nearly the same results or just slightly higher values that does not justify the higher amount of the additive. The fibers act as a cross linker between the cement particles and increase thereby the bonding. It seems that the root vegetable fibers induce a kind of flexibility to the cement matrix. The baseline is the same for every specimen set-up since ingredients, recipe, room temperature, curing time as well as the testing procedure are completely identical. The only difference between the neat Class G cube and the reinforced cube is that a maximum of 2.0 weight % of fibres are added to the second slurry type. The interpretation of the test results shows that compared to a neat class G sample, a 1.5wt% reinforced cube is able to increase the compressive strength of the cement by 0.8 tons after 24 hours of curing time. Taking the applied force and divide it by the cube area (50x50mm of 2"x2") the strength increases from 6.8 MPa or 968 psi (neat Class G cube) to 9.81 MPa or 1,423 psi (1.5wt% reinforced cube). Measuring the compressive strength after 48 hours, the additive is able to increase the resistance of the cement by 1.5 tons. The strength increases from 13.73 MPa or 1,992 psi (neat Class G cube) to 19.62 MPa or 2,847 psi (1.5wt% reinforced cube). After four days of curing time, following properties are measured. The red needle indicated a maximum applied force of 4.5 tons at the neat Class G sample, whereas the reinforced specimen was able to withstand a lever force of 5.6 tons. The strength increases from 17.66 MPa or 2,562 psi (neat Class G cube) to 22 MPa or 3,190 psi (1.5wt% reinforced cube). The 2 wt% results are not compared due to the above-mentioned reasons. The test results are also shown in Figure 79.

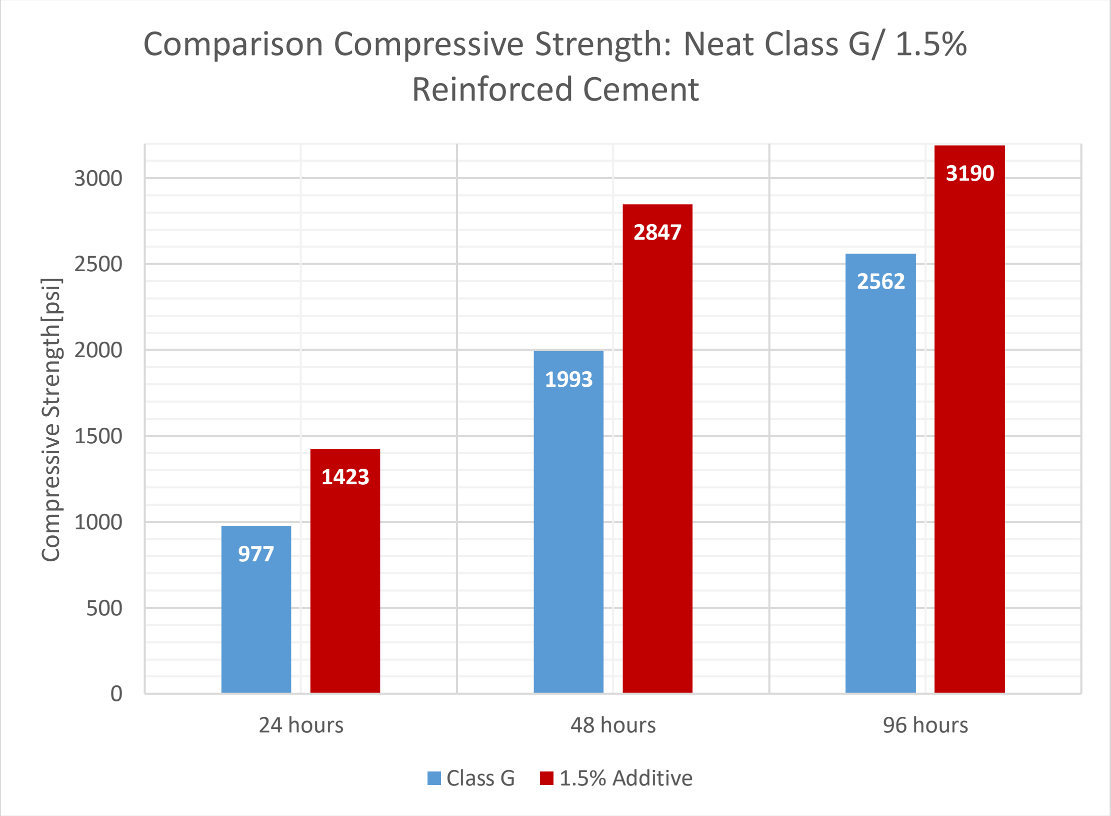


Figure 79: Test results of the compressive strength test
For the results the best performing slurry (1.5 wt% of fibres) is compared with the results from the neat Class G test

It can be stated, that the fibers increase the bonding efficiency between the cement particles, resulting in a higher compressive strength compared to the neat Class G cubes. This is also clearly indicated if the appearance of the specimens after crushing action is compared. The reinforced specimens maintain their structure and shape very well whereas neat Class G samples often break completely apart, or a high number of cement chips snapped against the wall of the test machine. The reinforced cubes are way less brittle and more compact. This indicates a better bonding between the cement particles. Figure 80 shows a neat Class G sample after the test and Figure 81 a fibre reinforced specimen. The two samples are from the same specimen set up, so density, curing time and all other properties are the same. The only difference is the additive that was added to the second cube shown in Figure 81.

Figure 80: Neat Class G sample after testing procedure
The picture shows the neat Class G sample after testing in the Carver Press. The specimen has a very brittle behaviour. This is indicated by many small chips and pieces of cement.

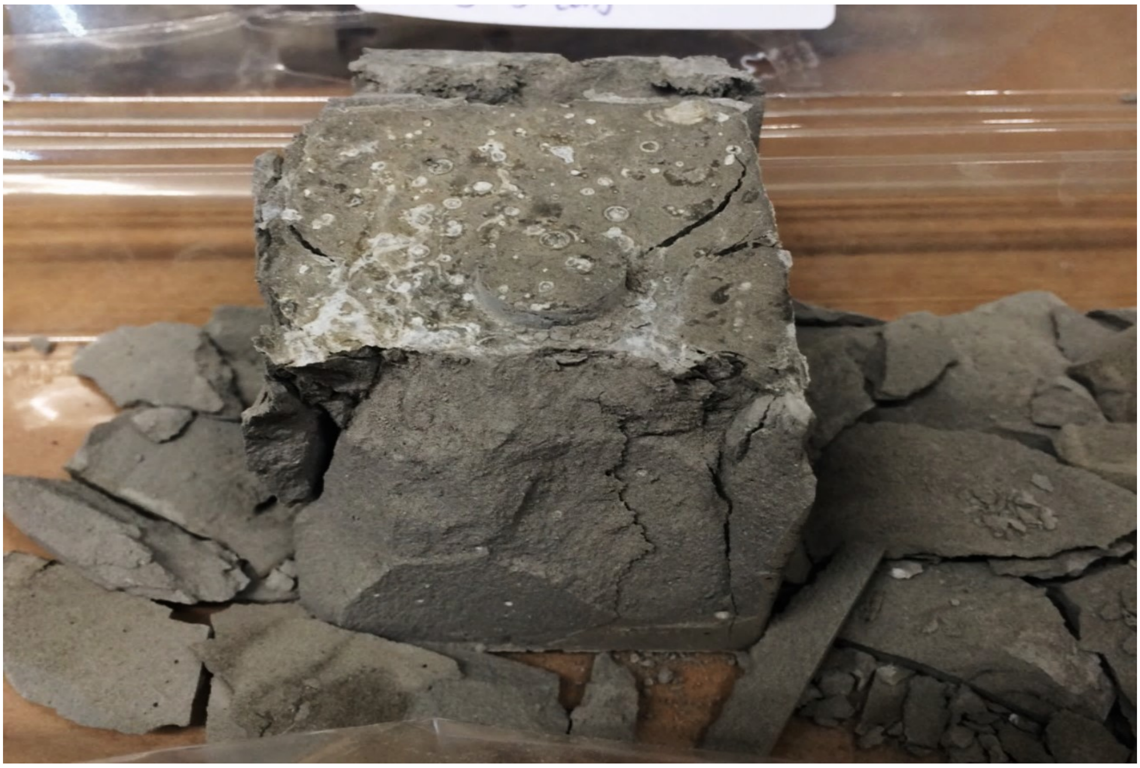


Figure 81: 1.5 wt% sample after testing procedure
The picture shows the 1.5 wt% sample after testing in the Carver Press. The specimen is more compact, flexible and less brittle. This is because of the improved bonding between the cement particles induced by the fibers.

To summarize it can be stated, that the compressive strength tests are successful. The additive seems to increase the strength of the cement matrix, at least for the tested 1753 kg/m^3 or 14.6 ppg slurry. The handling of the additive is very simple. No HSSE concerns pop up when one uses the additive, since all ingredients are from organic origin. The fibers form kind of bridges between the cement particles resulting in an increased flexibility of the specimen. Best test results could be achieved adding 1.5wt% of fibres to the slurry. A higher amount of additive is not recommended since compressive strength development is not increased as expected. Furthermore, preparing a cement slurry with a higher quantity than 1.5 wt% can cause troubles during mixing process. Adding 3 wt% makes it nearly impossible to produce a practical slurry. Further research must be done in order to evaluate the heat resistance as well as the compatibility between the additive and oil-based muds. It is suggested to perform further compressive strength test with lighter cement slurries and compare them with neat Class G samples of the same density. If one is able to create a formula that uses the fibres as a strengthening additive that shows similar compressive strength results as shown in Figure 78 but with a reduced density (e.g. 10 ppg), massive improvements regarding cement plugs issues (base fluid to slurry interface problems) or lost circulation prevention in weak formations etc. would be the result.

Chapter 7 Results and Discussion

7.1 Results and Discussion

Performing a successful cement plug job in order to sidetrack a wellbore on the first attempt is a challenge that the petroleum industry still focuses today. One main task of this master thesis is the implementation of a novel data analysis tool to simulate kick-off plug jobs on the paper and to evaluate the most important design factors for an effective cementing job.

The foundation for implementing the data analysis tool is a detailed root cause analysis. Several industry related papers and appropriate literature provide the basis for the assessment. In total 15 major industry relevant root causes could be classified and categorized. The issues address the most frequent problems that lead to cement plug failures. An assessment of the failure groups shows that approx. 46% of all kick-off plug failures are caused by slurry contamination. The contamination is triggered either by an instable interface between the plug base fluid and the cement slurry or by stinger pulling induced turbulences that lead to a mixture of the slurry and the drilling mud. Furthermore, the contamination reduces the compressive strength characteristics of the kick-off plug massively. These events could also be observed during the assessment of the laboratory conducted simulation runs, described in a separate paragraph. To summarize it can be stated that cement contamination and subsequent compressive strength reduction provoke more than 70% of all industry known kick-off plug issues. Research conducted by Nelson and Guillot (2006); Marriott et al. (2006); Beirute (1978); Crawshaw and Frigaard (1999) or Heathman and Carpenter (1994) confirm these findings. Further results of the detailed literature review show that inadequate cement volume calculations and insufficient mud cake removal contribute to an outage of the kick-off plug.

In order to implement the findings gathered in the research part as well as the root cause analysis of this thesis, a novel cement plug data analysis tool is designed. The methodology contains the invention as well as the confirmation of the software. The result of the development is a simple oilfield applicable program that is subdivided into four major modules starting with the calculation of the correct cement volume, followed by an assessment of the interface stability between the slurry and the base fluid. The third module covers the design of the right mud cake removal parameters and the fourth module contains the assessment of the selected tripping speed in order to evaluate predominant flow regime and swabbing induced pressures. One goal prior the development of the software was to keep it simple and straightforward in order to provide an intuitive tool that can be used on site as an ordinary survey or planning tool. This goal could be achieved since all necessary input parameters can be evaluated or calculated in small laboratories on the field. In total only seven different input parameters are required to evaluate all necessary design parameters. The input parameters are casing and drillpipe sizes, planned kick-off plug length, yield stresses, densities, viscosities, pump flow rate and drillpipe tripping speed. Since the invention of such a simplified data analysis tool for cement plugs is an innovation, no literature-based results are available that may confirm the quality of the program or prove the success of the theoretical assessed parameters. Therefore, laboratory-based simulations are conducted in order to check and test the prediction skills of the software. All input parameters as well as the predicted outcome of the software are listed in the corresponding Chapter 6. Using the design parameters of the program, four different kick-off plugs are produced. Table 20 compares the results of the laboratory simulation with the predicted results of the program:

Vertical Plug (Simulation No.1)			
Software	**Prediction**	**Simulation**	**Confirmed**
Slurry Volume	10.23 litres	Slurry Volume	✓
Interface Stability	Stable	Interface Stability	✓
Erodability		Erodability	—
Contamination	High	Contamination	✓
Deviated Plug (Simulation No.2)			
Software	**Prediction**	**Simulation**	**Confirmed**
Slurry Volume	10.23 litres	Slurry Volume	✓
Interface Stability	Instable	Interface Stability	✓
Erodability		Erodability	—
Contamination	High	Contamination	✓
Deviated Plug (Simulation No.3)			
Software	**Prediction**	**Simulation**	**Confirmed**
Slurry Volume	10.23 litres	Slurry Volume	✓
Interface Stability	Stable (Threshold)	Interface Stability	~
Erodability		Erodability	—
Contamination	Small	Contamination	~
Deviated Plug (Simulation No.4)			
Software	**Prediction**	**Simulation**	**Confirmed**
Slurry Volume	10.23 litres	Slurry Volume	✓
Interface Stability	Stable	Interface Stability	✓
Erodability		Erodability	—
Contamination	No	Contamination	✓

Table 20: Result comparison of software prediction and outcome of simulations

The erodability was not assessed in any simulation because of the smooth surface finishing of the Plexiglas pipes where the application of a drilling mud cake is impossible. The comparison between the investigated results of the software and the laboratory assessed outcomes show that the prediction quality of the program is accurate. The exact slurry volume calculation includes also stinger volume and an additional fraction for over displacement. The correct estimation of the over displacement volume could be observed in the last simulation run, where the recovery of the kick-off plug showed a cement filled stinger pipe. The correct predicted interface stability was monitored in three of four simulations. For the third run, a slightly stable fluid interface was predicted. During the experiment, the interface was stable as long as the wellbore was vertical but as soon as the borehole was tilted, the cement fell partly through the plug base. Nevertheless, the CT images of the third plug show less impact on the plug integrity as the visual inspection would assume. Therefore, the prediction quality of the interface stability in the threshold region is rated as acceptable and not assessed as a total failure of the software. In case that the data analysis tool predicts a design parameter as shown in Figure 63, it is recommended to change the variables of the input parameter in a way that a more stable fluid interface is achieved. One option is to increase the yield and adapt the density of the fluids or to use a diverter tool rather than an open-ended drillpipe. Regarding the contamination, predicted outcome of the third laboratory simulation and experimental achieved values also diverge. The observed contamination is less compared to the second simulation run, but regarding the design parameter fewer contamination was expected. It can be stated that a laminar flow regime extenuates the contamination effects since less turbulences cause less interference between the drilling mud and the slurry, but a laminar flow regime does not prevent any contamination. The additional use of a diverter tool is also recommended since the cement slurry escapes from the pipe in a more controlled way compared to an open-ended drillpipe design as it was used during the simulations. R. C. Smith (1984) also suggests the implementation of a diverter tool in order to improve the quality and success rate of cement plugs.

One major gole of the master thesis is the design and execution of a kick-off plug that is set successfully on the first attempt. In total four different cement plugs are planned and produced. Two of them (Simulation 1 and Simulation 2) were originally planned to fail (in order to test the failure prediction of the software) and two of them were planned to succeed (Simulation 3 and Simulation 4). The assessment of the simulation runs show that the first and the second cement plug failed as expected, whereas the first one indicates a stable cement base. The kick-off point of the first simulation is lower than planned since a major fraction of the slurry did not set and escaped with the drilling fluid from the pipe after pouring the mud out of the tube. The third simulation, as described above, also failed because of the instable plug base and the slightly higher observed contamination as expected. Nevertheless, it has to be mentioned that the design parameters were intentionally chosen in a way to test the threshold region. After evaluating the fourth simulation run, it can be stated that the laboratory simulation produced a successful kick-off plug. All attributes of the real plug match with the predicted design parameters of the software. The use of a sacrificial drillpipe is highly recommended since no turbulences are created that trigger any contamination. Less or no contamination result in an undamaged cement matrix that provide the compressive strenght necessary in order to sidetrack from the wellbore. The application of drillable aluminum pipes for balancing cement plugs is already described by Nelson and Guillot (2006) and confirms the observations monitored during the execution of the last simulation. The extent of the planned plug matches with the actual observed plug length and therefore increases the possibility to sidetrack from the planned kick-off point. To summarize it can be stated that the fourth kick-off plug, designed with the data analysis software and executed with the tools and worksteps described in the appropriate chapters is a cement plug that is set succesfully on the first attempt. It could be proven that the software is able to design plugs that fulfill all requirements to sidetrack a wellbore at the first time and therefore save useful manpower and money.

The prediction of the compressive strength of the cured cement is a challenge that depends on many variables such as temperature, pressure, location, slurry composition and specific downhole conditions. Because of the fact that the prediction might be accurate at surface conditions but not under downhole environmental influence (many papers that predict the compressive strength of cement refer to concrete specifics that were observed under surface conditions on the construction site or in the laboratory, rather than under oilfield conditions) it was decided to abstain from a compressive strength prediction in the software. Instead, separate experiments are conducted where the influence of a novel additive is investigated and rated against the compressive strength development of a neat Class G slurry. The results clearly indicate an increase of the compressive strength evolution if the additive is used. After 24 hours of curing time and using 1.5 wt% of the fibres a strength increase of 31% compared to a neat Class G sample is observed. After 48 hours an increase of 30% and after 96 hours the compressive strength is approx. 20% higher compared to a neat Class G cement cube cured under the same conditions. It is recommended to add a maximum of 1.5 wt% of the fibres to the slurry since a higher content triggers an immediate gelation of the cement that influences the pumpability and the placement of the slurry negatively. To summarize it can be stated that the fibres increase the compressive strength behaviour of the cement and additionally add some flexibility to the matrix that may be an advantage for kick-off plugs since a lesser brittle plug causes less problems and guides the drill bit more smoothly to the designated formation. To evaluate the influence of specific downhole environments (temperature, pressure, oil-based fluids, ...) on the additive, more experiments under the named conditions must be conducted.

The overall result of this thesis is the so called "House of Success" that is illustrated in Figure 82. The structure of the data analysis tool is based on the principle of the "House of Success". The building represents the individual components that are necessary in order to produce a successful kick-off plug. The investigation realized in this master thesis helped to break down a complex problem like the successful implementation of a cement plug, into four particular segments. The base of the houe is the right calculation of the "Cement Volume" that is required to place the plug in the wellbore. If already the estimation of the volume is incorrect, the house will collapes and the job might fail. In case that the basement is stable (the right volume is estimeted) three specific supports are required in order to place the roof on the structure. One of the modules is the "Plug Base Design". The correct assessment of the plug base is a key requirement for a successful cement plug. If the density difference between base fluid and the cement and/or the interface stability between the fluids is insufficient, one will fail to produce a working kick-off base. The second support is the "Mud Removal Design"- an often underestimated topic regarding the assessment of a cement plug. Only few papers deal with that subject (e.g. K. M. Ravi, Beirute, and Covington (1992)) but during research it turned out that that subject is a very important key factor that highly influence the success rate of cement plugs. The last and one of the most important supports of the house is the "Pull Rate Design". The pull rate determines the contamination of the cement slurry since stinger pulling induced turbulences and swabbing pressures cause a mixture of the cement and the drilling mud. Once the cement is contaminated, the curing time is dramatically increased or even the cement will not set at all. This phenomenon could also be observed during the execution of the simulations conducted in the laboratory. If all components are heeded with respect to downhole environment and wellbore conditions, one will be able to set a protective roof on top of the structure and gain a successful kick-off base that is set on the first attempt.

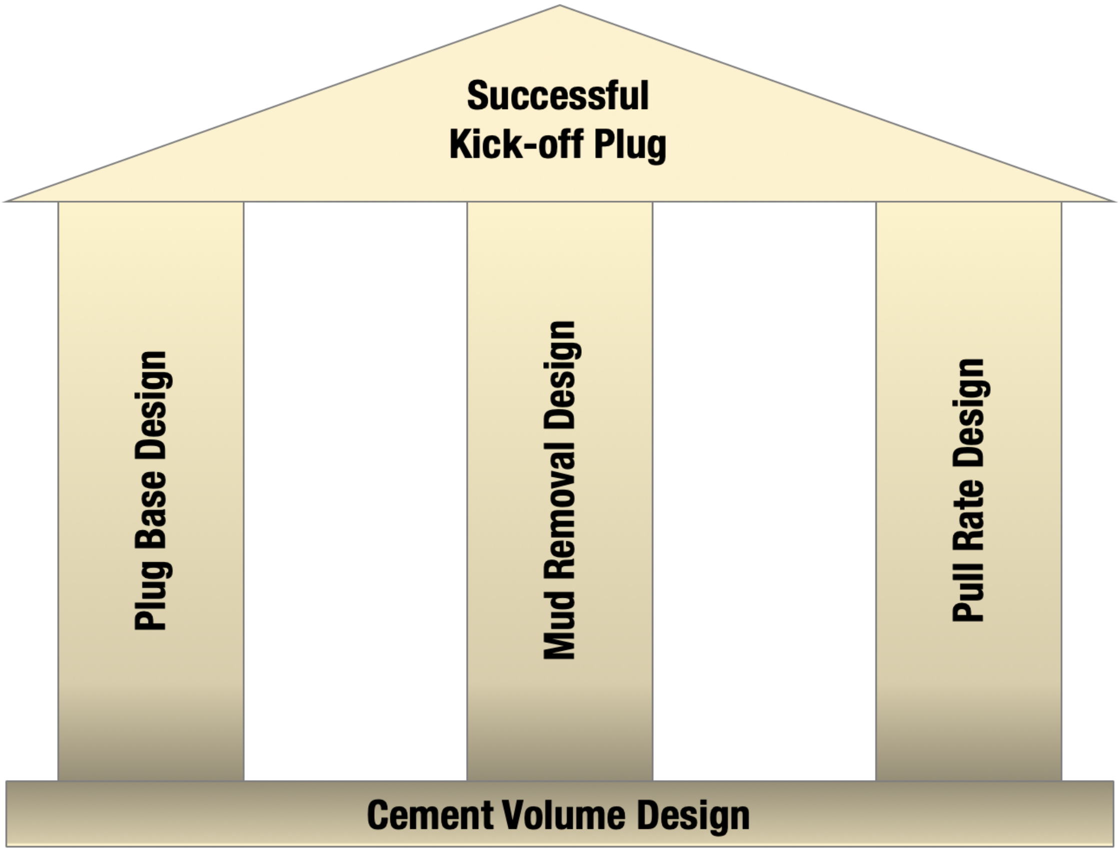


Figure 82: House of Success
The house of success represents the four essential modules needed, in order to produce a successful kick-off plug. The structure of the data analysis tool is based on the principle of the house of success.

7.2 Future work

The application of the data analysis tool under laboratory conditions is already tested and proved. In a next step it is recommended to test the program under field conditions and if necessary, adapt some parameters to the specifics of the operator. If this step is conducted, the program can be simplified and converted from an excel based software to a mobile phone employable application (App).

It is recommended to evaluate and compare the influence of the fibre additive on the compressive strength behaviour of the cement slurry under simulated downhole conditions (increased temperature, pressure and other specifics such as oil-based drilling mud). If these tests are a success, laboratory-based kick-off plugs can be produced (using the same conditions and tools as described in (Chapter 6), evaluated and compared with the test results obtained in the previous chapters. Big improvements can be achieved if the additive allows the production of cement plugs with a light weight slurry and simultaneously attaining the same or higher compressive strength values compared to a denser neat Class G cement. The light weight but improved strength characteristic would reduce the plug base instability problem dramatically (no slumping phenomenon) and decrease at the same time the amount of dry cement prior blending process.

Chapter 8 Conclusion

Today, one of the major challenges of the oil and gas industry is to explore new hydrocarbon resources and simultaneously keep the costs of such operations as low as possible or within a certain limit. Sometimes, geological circumstances or drilling induced issues require a sidetracking operation of an existing wellbore. On the one hand because it is more cost effective to explore from old wellbores and on the other hand because an obstacle such as a fish or weak formations hinder the operator to continue with the planned drilling job. In order to sidetrack a borehole a so-called cement plug is set at the designated location. From that point on, the compressive strength of the plug guides the drill bit into the desired direction and kicks-off the wellbore from that position. Research shows, that an industry average of 2.4 attempts are necessary until a well is side-tracked successfully. The reasons for that number are versatile but more than 70% of all cement plugs suffer from contamination effects that reduce on the one hand the compressive strength characteristics of the cement or hinders in general the formation of a usable kick-off base. The implementation of a data analysis tool should help to design a kick-off plug that fulfils all requirements in order to sidetrack the well successfully on the first attempt. The selective application of such a software reduces drilling costs and rig time and eventually improve the safety of the whole operation.

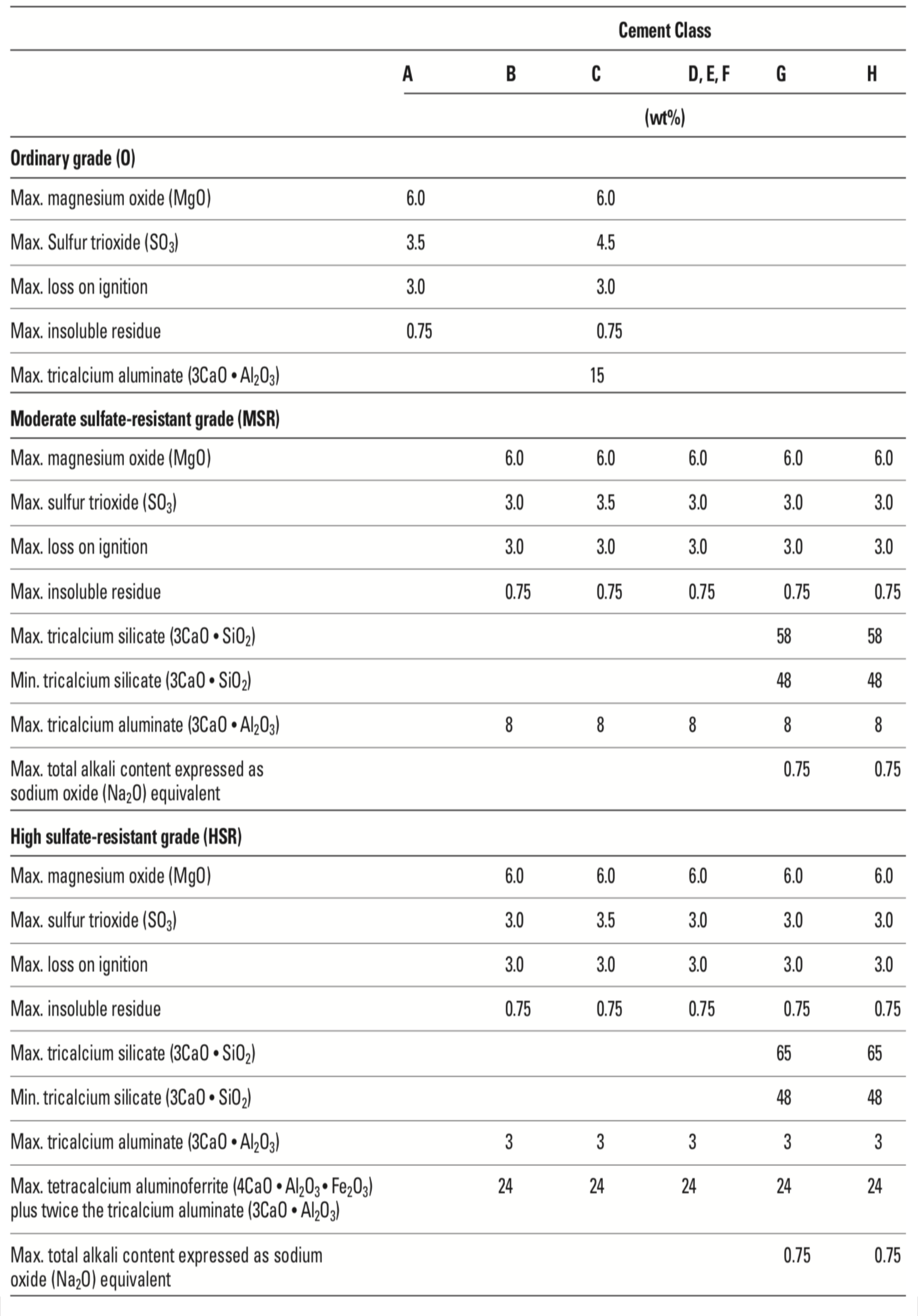
This thesis covers the methodology of the development of a data analysis tool that can be used to design cement plugs, to be more specific- kick-off plugs and simulate the consequence of specific fluid rheological parameters as well as distinctive selected drilling parameters on the outcome of the plug job. The foundation for the deployment of the software is a detailed root cause analysis that covers the most important issues with respect to cement plug failures. Based on the findings, the four most prominent influencing factors are selected and implemented into the structure of the software. To summarize it can be stated that the right volume estimation, plug base design, mud removal design as well as a detailed pipe pulling evaluation influences the success rate of a cement plug on a high level. It can be concluded, that the more accurate the assessment in the forefront is, the better are the chances to produce a practical kick-off base. In order to evaluate the prediction quality of the data analysis software, several laboratory-based simulations and experiments are conducted.

With respect to the outcomes and findings of the experiments, it can be stated that the prediction quality of the software is verified using lab simulations and literature data. Some divergences between predicted outcome and the laboratory-based simulations are recognized if the output parameters of the data analysis tool are located in a threshold region. If this is the case, input results must be changed in order to shift the design parameter into a safe region. The prediction quality of the compressive strength of a cured cement plug in a wellbore is not reliable, since many parameters influence the outcome of the predicted design parameter. Some of the influencing factors might change between different hydrocarbon fields or even within the length of a wellbore. Therefore, no compressive strength module is added to the design software. In return a novel strengthening additive is tested and evaluated. It can be stated that the fibre-based additive improves the compressive strength quality of a neat Class G sample and is therefore recommended and could be used as a cost-effective supplement.

Using the developed data analysis software as a design tool for planning kick-off plugs will increase the success-rate for cement plugs. The tool is not tested under real field conditions, but the program output is compared with the result of laboratory-based simulations.

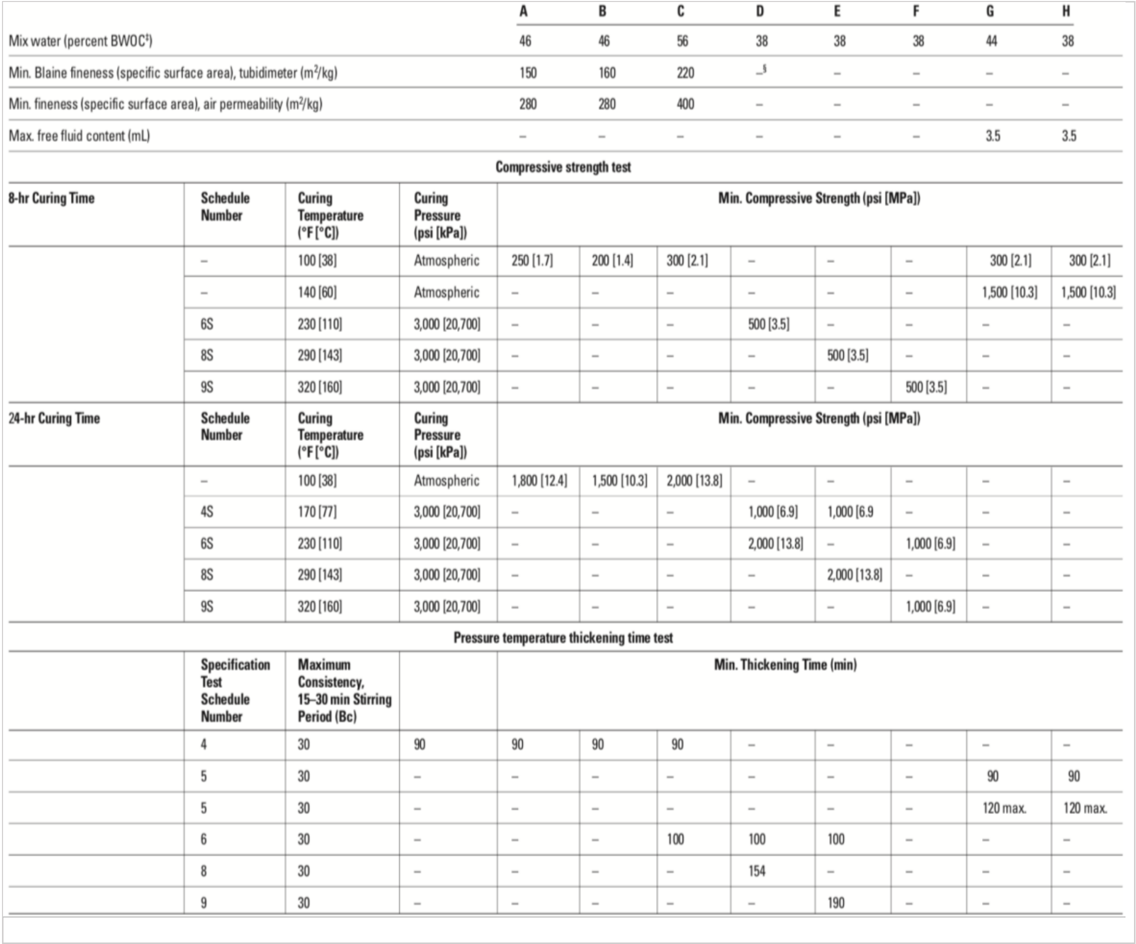
Some important topics that are not covered by this thesis are the implementation of the software into a real field job and the transformation into a mobile phone-based app. Furthermore, the fibre additive is not tested under the influence of field conditions as well as a supplement in light weight slurries.

Appendix



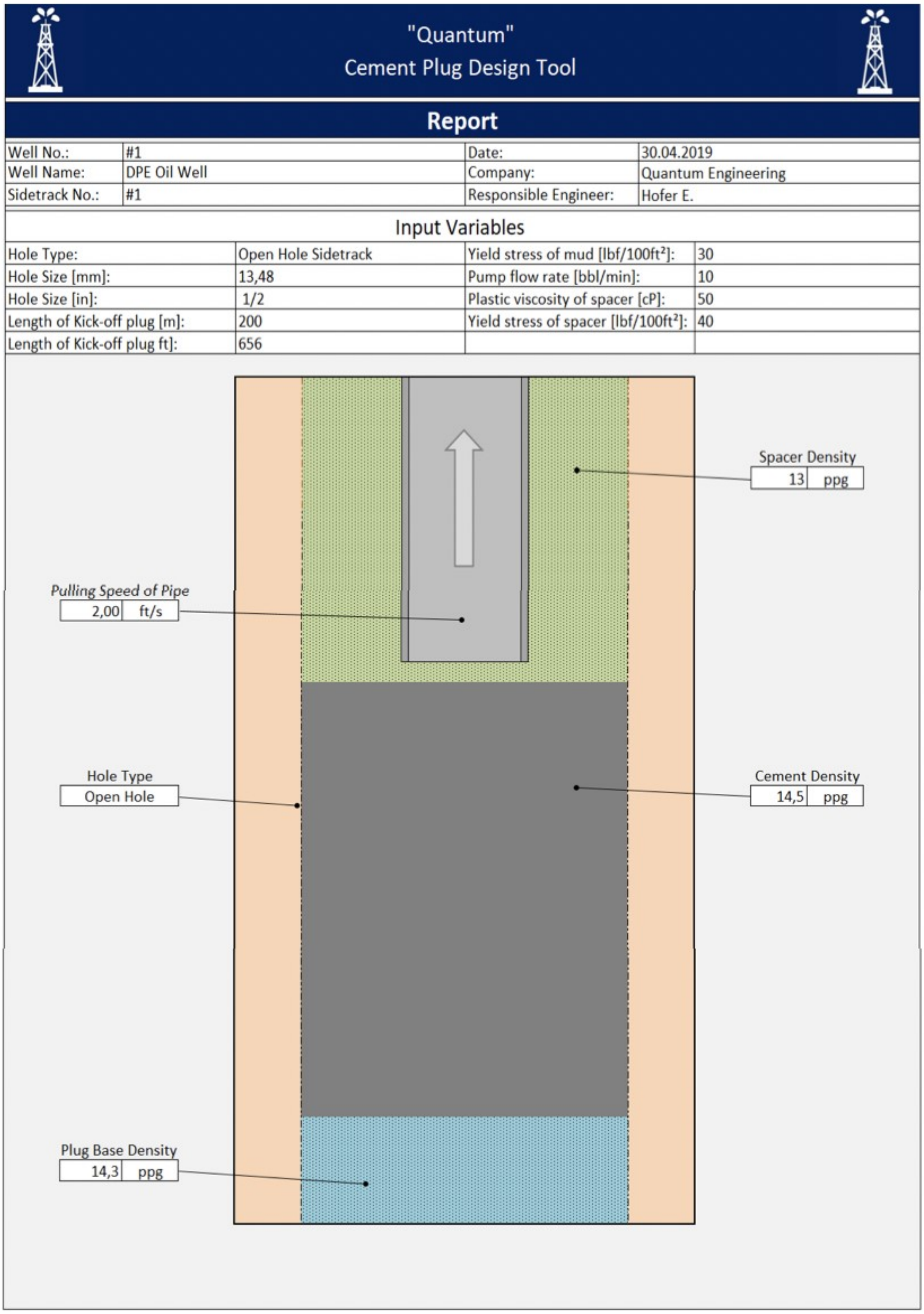
	Cement Class					
	A	B	C	D, E, F	G	H
	(wt%)					
Ordinary grade (O)						
Max. magnesium oxide (MgO)	6.0		6.0			
Max. Sulfur trioxide (SO_3)	3.5		4.5			
Max. loss on ignition	3.0		3.0			
Max. insoluble residue	0.75		0.75			
Max. tricalcium aluminate ($3CaO \cdot Al_2O_3$)			15			
Moderate sulfate-resistant grade (MSR)						
Max. magnesium oxide (MgO)		6.0	6.0	6.0	6.0	6.0
Max. sulfur trioxide (SO_3)		3.0	3.5	3.0	3.0	3.0
Max. loss on ignition		3.0	3.0	3.0	3.0	3.0
Max. insoluble residue		0.75	0.75	0.75	0.75	0.75
Max. tricalcium silicate ($3CaO \cdot SiO_2$)					58	58
Min. tricalcium silicate ($3CaO \cdot SiO_2$)					48	48
Max. tricalcium aluminate ($3CaO \cdot Al_2O_3$)		8	8	8	8	8
Max. total alkali content expressed as sodium oxide (Na_2O) equivalent					0.75	0.75
High sulfate-resistant grade (HSR)						
Max. magnesium oxide (MgO)		6.0	6.0	6.0	6.0	6.0
Max. sulfur trioxide (SO_3)		3.0	3.5	3.0	3.0	3.0
Max. loss on ignition		3.0	3.0	3.0	3.0	3.0
Max. insoluble residue		0.75	0.75	0.75	0.75	0.75
Max. tricalcium silicate ($3CaO \cdot SiO_2$)					65	65
Min. tricalcium silicate ($3CaO \cdot SiO_2$)					48	48
Max. tricalcium aluminate ($3CaO \cdot Al_2O_3$)		3	3	3	3	3
Max. tetracalcium aluminoferrite ($4CaO \cdot Al_2O_3 \cdot Fe_2O_3$) plus twice the tricalcium aluminate ($3CaO \cdot Al_2O_3$)		24	24	24	24	24
Max. total alkali content expressed as sodium oxide (Na_2O) equivalent					0.75	0.75

Figure 83: API oilfield cement specifics (1)
cf. Nelson and Guillot (2006)



				A	B	C	D	E	F	G	H
Mix water (percent BWOC[‡])				46	46	56	38	38	38	44	38
Min. Blaine fineness (specific surface area), tubidimeter (m^2/kg)				150	160	220	–[§]	–	–	–	–
Min. fineness (specific surface area), air permeability (m^2/kg)				280	280	400	–	–	–	–	–
Max. free fluid content (mL)				–	–	–	–	–	–	3.5	3.5
Compressive strength test											
8-hr Curing Time	**Schedule Number**	**Curing Temperature (°F [°C])**	**Curing Pressure (psi [kPa])**	**Min. Compressive Strength (psi [MPa])**							
	–	100 [38]	Atmospheric	250 [1.7]	200 [1.4]	300 [2.1]	–	–	–	300 [2.1]	300 [2.1]
	–	140 [60]	Atmospheric	–	–	–	–	–	–	1,500 [10.3]	1,500 [10.3]
	6S	230 [110]	3,000 [20,700]	–	–	–	500 [3.5]	–	–	–	–
	8S	290 [143]	3,000 [20,700]	–	–	–	–	500 [3.5]	–	–	–
	9S	320 [160]	3,000 [20,700]	–	–	–	–	–	500 [3.5]	–	–
24-hr Curing Time	**Schedule Number**	**Curing Temperature (°F [°C])**	**Curing Pressure (psi [kPa])**	**Min. Compressive Strength (psi [MPa])**							
	–	100 [38]	Atmospheric	1,800 [12.4]	1,500 [10.3]	2,000 [13.8]	–	–	–	–	–
	4S	170 [77]	3,000 [20,700]	–	–	–	1,000 [6.9]	1,000 [6.9	–	–	–
	6S	230 [110]	3,000 [20,700]	–	–	–	2,000 [13.8]	–	1,000 [6.9]	–	–
	8S	290 [143]	3,000 [20,700]	–	–	–	–	2,000 [13.8]	–	–	–
	9S	320 [160]	3,000 [20,700]	–	–	–	–	–	1,000 [6.9]	–	–
Pressure temperature thickening time test											
	Specification Test Schedule Number	**Maximum Consistency, 15–30 min Stirring Period (Bc)**		**Min. Thickening Time (min)**							
	4	30	90	90	90	90	–	–	–	–	–
	5	30	–	–	–	–	–	–	–	90	90
	5	30	–	–	–	–	–	–	–	120 max.	120 max.
	6	30	–	–	–	100	100	100	–	–	–
	8	30	–	–	–	–	154	–	–	–	–
	9	30	–	–	–	–	–	190	–	–	–

Figure 84: API oilfield cement specifics (2)
cf. Nelson and Guillot (2006)



"Quantum"
Cement Plug Design Tool

Report

Well No.:	#1	Date:	30.04.2019
Well Name:	DPE Oil Well	Company:	Quantum Engineering
Sidetrack No.:	#1	Responsible Engineer:	Hofer E.

Input Variables

Hole Type:	Open Hole Sidetrack	Yield stress of mud [lbf/100ft²]:	30
Hole Size [mm]:	13,48	Pump flow rate [bbl/min]:	10
Hole Size [in]:	1/2	Plastic viscosity of spacer [cP]:	50
Length of Kick-off plug [m]:	200	Yield stress of spacer [lbf/100ft²]:	40
Length of Kick-off plug ft]:	656		

Spacer Density 13 ppg

Pulling Speed of Pipe 2,00 ft/s

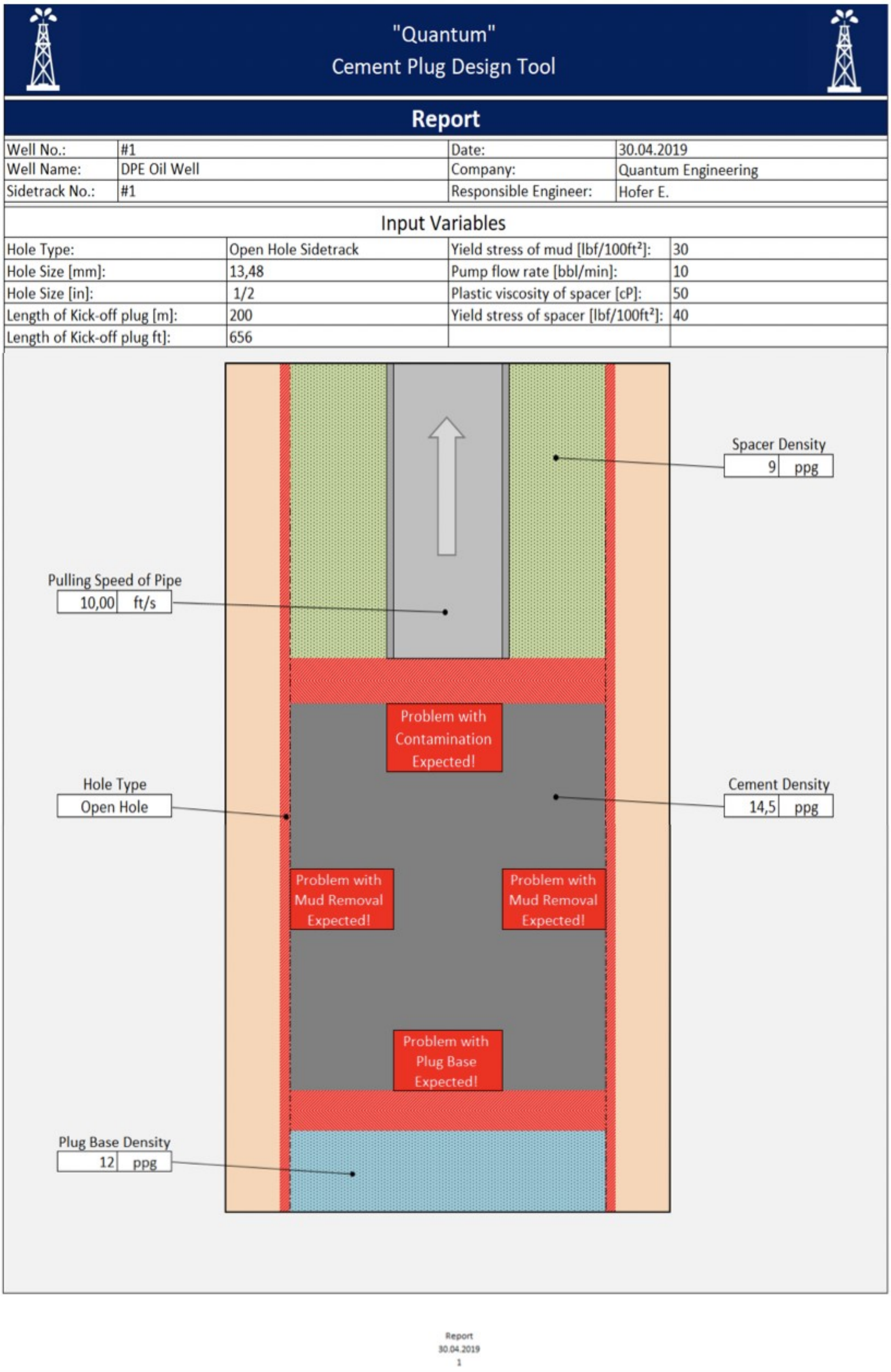
Hole Type Open Hole

Cement Density 14,5 ppg

Plug Base Density 14,3 ppg

Report
30.04.2019
1

Figure 85: Report of the Data Analysis Tool (Plug without predicted problems)



"Quantum"
Cement Plug Design Tool

Report

Well No.:	#1	Date:	30.04.2019
Well Name:	DPE Oil Well	Company:	Quantum Engineering
Sidetrack No.:	#1	Responsible Engineer:	Hofer E.

Input Variables

Hole Type:	Open Hole Sidetrack	Yield stress of mud [lbf/100ft²]:	30
Hole Size [mm]:	13,48	Pump flow rate [bbl/min]:	10
Hole Size [in]:	1/2	Plastic viscosity of spacer [cP]:	50
Length of Kick-off plug [m]:	200	Yield stress of spacer [lbf/100ft²]:	40
Length of Kick-off plug ft]:	656		

Spacer Density 9 ppg

Pulling Speed of Pipe 10,00 ft/s

Problem with Contamination Expected!

Hole Type Open Hole

Cement Density 14,5 ppg

Problem with Mud Removal Expected!

Problem with Mud Removal Expected!

Problem with Plug Base Expected!

Plug Base Density 12 ppg

Report
30.04.2019
1

Figure 86: Report of the Data Analysis Tool (Plug with several predicted issues)

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Acronyms

AC	Alternating Current
API	American Petroleum Institute
BHA	Bottom Hole Assembly
BHCT	Bottom Hole Circulation Temperature
BHST	Bottom Hole Static Temperature
BOP	Blow-out Preventer
BPM	Balanced Plug Method
CH	Cased Hole
CT	Coiled Tubing
DP	Drillpipe
DS	Drillstring
EOR	Enhanced Oil Recovery
ERW	Extended Reach Well
HPHT	High Pressure High Temperature
HSR	High Sulfate Resistance
ID	Inner Diameter
KPIs	Key Performance Indicators
LC	Lost Circulation
LCM	Lost Circulation Material
LT	Lost-Time
MSR	Moderate Sulfate Resistance
NPT	Non-Productive Time
O	Ordinary
OD	Outer Diameter
OH	Open Hole
OHWBE	Open Hole to Surface Well Barrier Element
P&A	Plugging and Abandonment
PA	Permanent Abandonment
POOH	Pulling Out of Hole
RIH	Run in Hole
ROP	Rate of Penetration

RPM	Revolutions per Minute
SBM	Synthetic Based Mud
TA	Temporary Abandonment
TD	Total Depth
TOC	Top of Cement
WB	Well Barrier
WBE	Well Barrier Element
WOB	Weight on Bit
WOC	Wait on Cement
XT	X-Mas Tree

Symbols

α_c	Critical Alpha value	[-]
D	Diameter	[mm or in]
E	Erodability	[-]
f	Friction factor	[-]
l	Length	[m or ft]
m	Mass	[kg]
μ	Plastic viscosity	[mPa*s or cP]
N_{He}	Hedstrom Number	[-]
N_{Rep}	Reynolds Number	[-]
$N_{Rep,critical}$	Critical Reynolds Number	[-]
p	Pressure	[Pa/bar or psi]
δ	Density	[kg/m^3 or lbf/gal or ppg]
τ	Yield stress	[Pa or lbf/100ft^2]
V	Volume	[m^3 or gal]
v	Velocity	[m/sec or ft/sec]

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