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Evidences of Poor Cement Displacement Jobs

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Abstract

Cementing operation is one of the most challenging tasks in the completion phase of oil and gas wells. Many problems here are related to cement- displacement process, blending, additives, and the entire design of the cementing operation. Failure of primary cement jobs leads to expensive remedial cementing work like squeezing and plugging.

This thesis work was focused in finding evidences of poor cement displacement jobs by considering three basic quantities related to cement displacement namely; the annular volume to be cemented, volume of cement pumped and the resulting height of cement in the annulus. Five successful- and four failed cement jobs (cases) were used to accomplish this study. The analysis (calculations and ontology engineering) of all failed cases was done using excel software.

Well schematics for planned and completed cement jobs were also presented for each case to verify the existence of poor cement jobs (for failed cases) and of good cement jobs (for successful cases).

Enhanced understanding and knowledge of well cementing operation found through this study is helpful in forecasting similar failures in future cement jobs and hence reduce the failures related to the cement displacement process and the associated costs of remedial jobs.

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1. Introduction

Poor cement jobs in completion of oil and gas wells have been a challenge for decades. Displacement of mud by cement slurry during cementing operation is a key factor for ensuring proper isolation of zones. It is shown by actual well tests that the majority of wells have zonal communication during their production life-time. Zonal communication may allow contact between formation fluids like water/gas and oil, this greatly affect oil production and expensive remedial actions like squeeze cementing may be required (Chen, Chaudhary, & Shine, 2014).

Another important factor for zonal isolation is proper removal of mud cakes, if left between set cement and permeable formations, they provide for the passage of water and/or gas which leads to failures of cement jobs (Jones & Berdine, 1940).

Improper mud and mud cake displacement can be caused by many factors like (Eberhardt & Shine Jr, 2004; Jones & Berdine, 1940; McLean et al., 1967; R. Smith, 1984; T. Smith & Ravi, 1991):

- Eccentric annulus
- Cement slurry flow regime (pattern)
- Mud rheology
- Running in casing without scrapers or applying other means of removing mud cakes
- Cementing technology applied.

The main challenge to petroleum industry has, however, been how to attain a good cement displacement job during completion of oil and gas wells. Some of the methods to ensure good cement jobs and hence reduce or eliminate unnecessary downtime and its associated costs are such as (Eberhardt & Shine Jr, 2004; McLean et al., 1967; R. Smith, 1984; T. Smith & Ravi, 1991):

- Use of centralizers when running in casings
- Run casing with scratchers, hydraulic jetting or treatment with acids
- Thinning the mud before running in casing
- Isolating cement by plugs when pumping down
- Establishing turbulent- or plug flow of cement slurry

The main goal of this study is to enhance the understanding of the cement job in order to reduce cement job failures.

The specific objectives are therefore to find field evidence of poor cements displacement jobs and to quantify it, especially in extended reach wells and slim-hole wells by focusing on:

- How large was the volume to be cemented (space between wellbore wall and casing)
- How large a volume of cement was injected to fill the space
- How far up in the annulus did high quality cement reach

The goals will be achieved through first building understanding of the general knowledge of cementing and cement displacement from literature, followed by finding data in the field which will be used to quantify the evidence of poor cement displacement jobs. Through these activities the insight of the problem in question will be improved.

The challenge to be solved in this work is summarized schematically in Figure 1. The Figure is also used as a reference for describing some basic cementing terminologies in chapter 2.

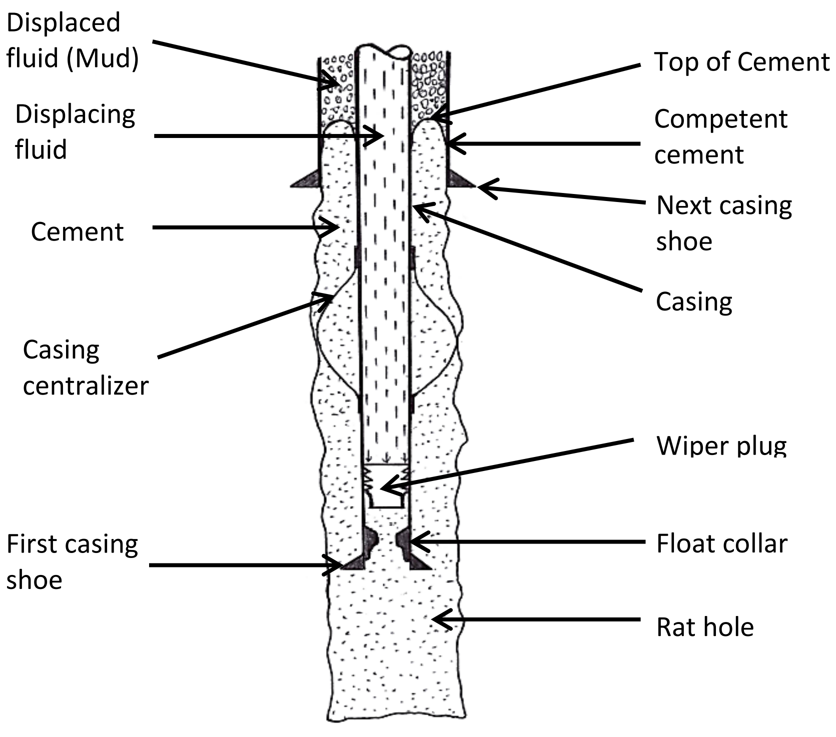

Figure 1: *Schematic presentation of cementing operations*

2. Previous published relevant knowledge

In this thesis work, several technical terms relating to cementing operation are used throughout the study and findings without their description. For this matter, the reader is introduced to some basic and important cementing terminologies in order to be aware of what is meant by the particular term(s) and keep in pace with the work.

2.1. Basic Cementing Terminologies

Well cementing. Whether a well is for the purpose of producing hydrocarbons or injection of fluids, proper cementing is necessary in order to provide a hydraulic seal between formation and casing pipe, to protect- and support the casing pipe and to isolate production zones (Sauer & Landrum, 1985). Basing on aim of cementing, there are two types of well cementing which are primary and secondary (or remedial) cementing operation (Henriksen, 2013).

Primary cementing is the process of placing cement slurry in the annulus between the casing and the formation exposed to the wellbore. In hydrocarbons industry, it was invented in the year 1903 (Nelson, 1990). When correctly performed, it must achieve complete zonal isolation in the wellbore by providing a sufficient hydraulic seal between casing and formation while at the same time eliminating mud or gas channels within the cement sheath (R. Smith, 1984). Figure 2 shows how casing is cemented for the first time in the wellbore and achieve primary cementing objectives.

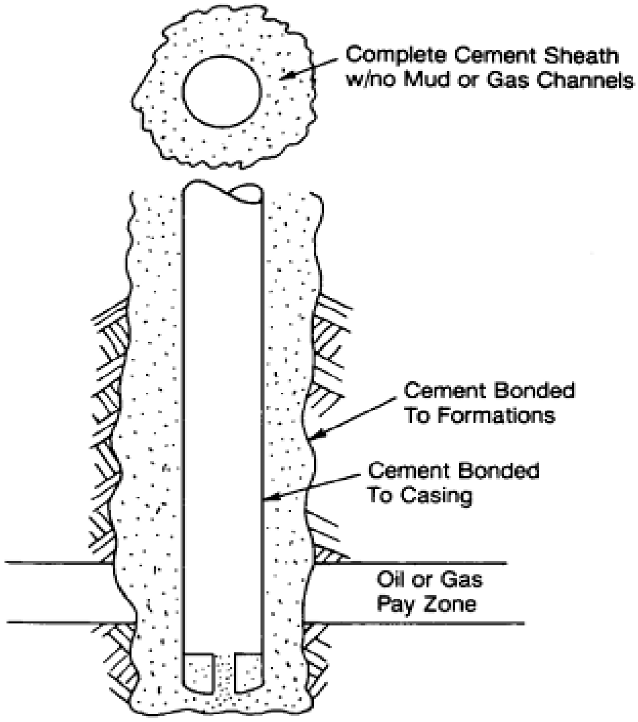

Figure 2: *Sketch of primary cementing job (R. Smith, 1984)*

Secondary cementing is a remedial cementing operation which is done to correct problems associated with poor primary cement job. There are two main types of secondary cementing jobs namely; Squeeze cementing and Plug cementing (Nelson, 1990).

Squeeze cementing is the process of forcing cement slurry (at high pressure) into the perforations in the casing and behind the casing. It is commonly done to serve one or more than one of the following purposes (Toor, 1983):

- Repair a primary cement job that has failed due to cement by-passing mud (channeling) or insufficient height (fill up) in the annulus

- Eliminate water intrusion from above, below or within the hydrocarbon producing zone
- Reduce the producing gas-oil ratio (GOR) by isolating gas zones from adjacent oil intervals
- Repair casing leaks due to corrosion or split pipe
- Plug all, or part, of one or more zones in a multi-zone injection well to direct injection into desired intervals, and
- Plug and abandon a depleted or watered out producing zone.

Plug cementing is a technique used to stop the flow of fluids from one formation to another in a well or from formations to the surface by placing a smaller amount of cement at a specific position in the well (Henriksen, 2013; Nelson, 1990). Scenarios that necessitate use of this technique are well abandonment, sidetracking and lost-circulation control.

Another well recompleting technique which is popular in off-shore Gulf of Mexico (GoM) for recompletion of bypassed sands during the original completion (primary cementing) is *Liquid Cement Premix (LCP)*. It is completed using cement packer and hence results in opportunities for new production that in some cases can surpass the original completion peak production (Eberhardt & Shine Jr, 2004).

Cement slurry is the fine division of solid particles (cement and solid additives) dispersed in a liquid (Toor, 1983). For primary cementing it is used to fill the space between casing pipe and formation whereas for secondary cementing operation (squeeze cementing) it is forced into production perforations to cure the problem of high water or high GOR in the produced oil or any other problem as a result of poor primary cement job (Toor, 1983).

Cement additives are substances commonly added to cement slurry to achieve the desired slurry properties (Skalle, 2014b). Cement additives have played an important role in advancement of cementing technology (Nelson, 1990). The commonly used cement additives are as described in Table 1.

Table 1: Examples of cement additives with their effects on cement slurry (Nelson, 1990; Skalle, 2014b)

Additive Category	Benefit or effect on Slurry
Accelerator	• Shorter thickening time • Higher early compressive strength
Retarder	• Longer thickening time
Extender	• Lower slurry density • Higher slurry yield
Weighting agent	• Higher slurry density
Dispersant	• Lower slurry viscosity
Fluid-loss additives	• Reduce slurry dehydration
Lost circulation control agent	• Prevent loss of slurry to formation
Specialty additives	• Antifoam agents • Fibres, etc

Top of cement (TOC) is the depth (MD or TVD) measured from surface to where high quality cement slurry has reached when rising in the annulus during primary cementing operation (Chen et al., 2014). The TOC is usually determined by Cement bond logs (CBL), Temperature logs or similar tools.

Rat hole is the open wellbore section (length) remaining after cementing the casing. It is measured from the first casing shoe to the bottom of the well as seen in Figure 1.

Casing centralizers are bow–like devices with both ends fixed on the outside wall of the casing to serve two purposes; to clean wellbore (aid in removing mud cake) and to ensure that the casing string is centered relative to the wellbore (Jones & Berdine, 1940). Casing centralizers are important to ensure good cement displacement during cementing operation. Figure 3 presents a clear pictorial view of the casing centralizers.

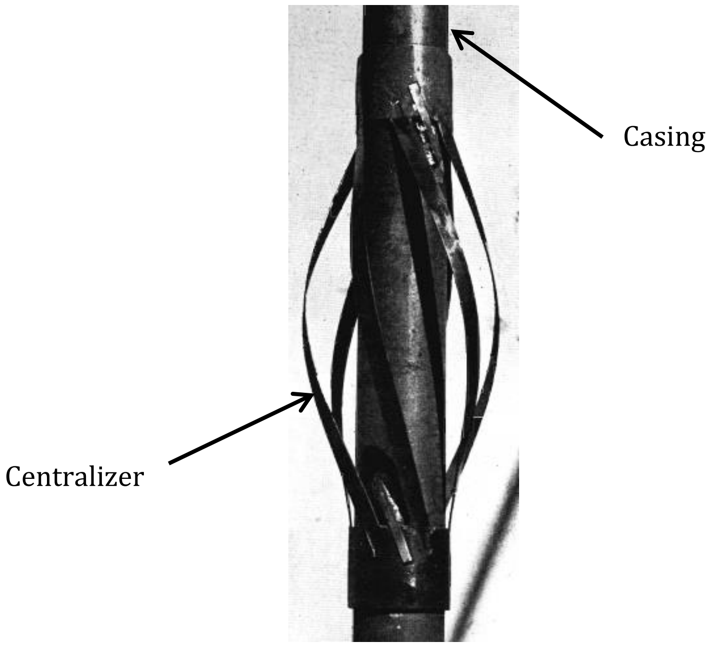

Figure 3: *Casing Centralizers (Jones & Berdine, 1940)*

Scratchers; Mechanical scratchers are usually fixed onto the casing outside wall for the purpose of rubbing against wellbore wall when casing is rotated and moved axially. Scratchers remove any mud cake in the permeable formations leading to good cement bond with the formation. Typical Scratchers are shown Figure 4.

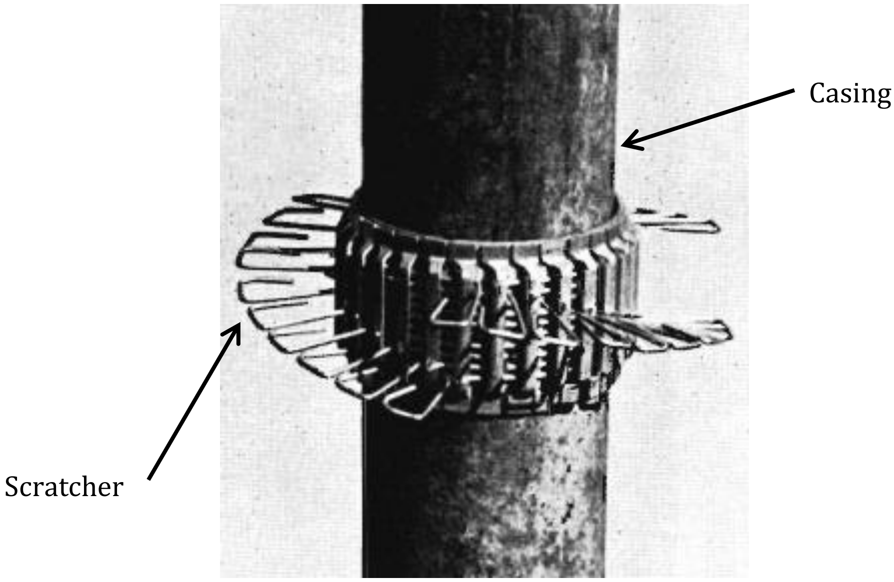

Figure 4: *Mechanical Scratchers (Jones & Berdine, 1940)*

Cement-bond logs (CBL): This is one of the cement sheath evaluation techniques that are done by running wireline tools into a cased hole and interpreting the results. The CBL is used to determine if there is proper isolation of zones in the cemented well. That is, quality or condition of cements (channeling, gas-cut or dehydrated cements and microannulus) and the bond quality for both between casings with cement and cement with wellbore wall. CBL is also useful to locate TOC (Benge, 2014).

The basic theories or interpretation rules of CBL in evaluating cement integrity are (Crain, 1978):

- *Rule 1*: Low amplitude = Good cement
- *Rule 2*: High attenuation = Good cement

- *Rule 3*: High bond index = Good cement

An example of CBL showing good and poor cement intervals is shown in Figure 5. The log shows good bond over the oil and water zones and bad/poor cement over the gas bearing zone. This is probably due to percolation of gas into the cement during the curing process (Crain, 1978).

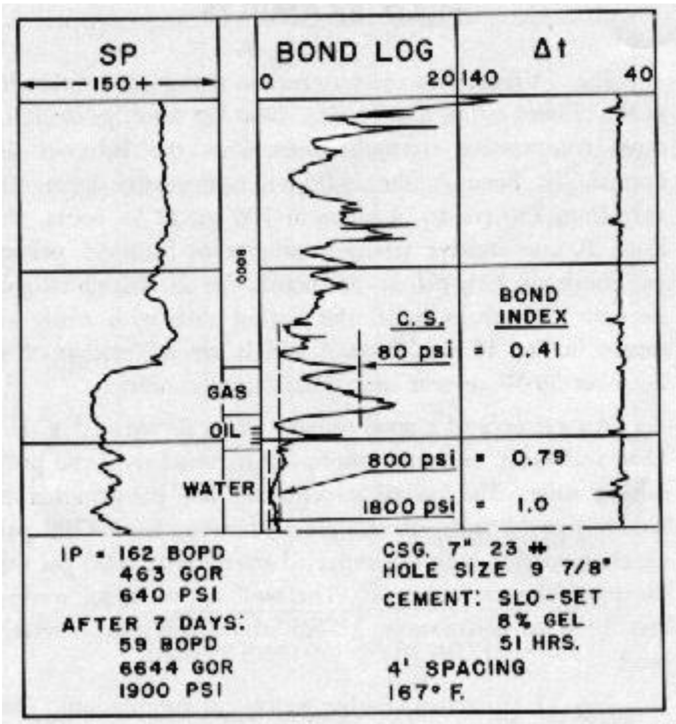

Figure 5: *CBL showing good and bad cement bond in the logged interval (Crain, 1978)*

Apart from CBL technique, other techniques used for evaluating integrity of the cements include (Benge, 2014; Crain, 1978; Hayden et al., 2011):

- Cement mapping Logs (CMT)
- Ultrasonic cement mapping tool (CET)
- Ultrasonic Imaging Logs (USI)
- Cement Bond Log with Variable Density Logs (CBL-VDL)
- Temperature Logs for locating TOC
- Flexural Attenuation Map
- Understanding objectives of the cement job. For example, if the job objective is to have pressure isolation at the casing shoe so that subsequent drilling continues for next section, then the evaluation technique may simply be a pressure test. Similarly, TOC can be determined by pressure matches with job data
- Understanding design limitations imposed by the objective(s)
- Resulting cement slurry. Once the slurry is blended and pumped, the returns can be used to evaluate the condition of down hole cement
- Cement job design.

2.2. Poor cement jobs

Competent cementing to achieve a long-lasting zonal isolation is a crucial requirement during completion of hydrocarbon wells (Nair, Wu, Cowan, & van Oort, 2015).

Poor cement jobs in completion of hydrocarbon wells lead to improper isolation of production zones and hence failure of the cement job. It is also a source of problems like high producing GOR, high proportion of water in produced oil and corrosion of casing strings. The consequences of these abnormalities can be dire and necessitate costly extensive remedial recompletion operations like squeeze cementing to cure the problem (Chen et al., 2014; Nair et al., 2015).

Further, poor cement job is the lead cause of off-shore well blow-outs, the April 20th, 2010 Macondo blow-out in the off-shore GoM and the August 21st, 2009 blow-out in Montara western Australia are examples (Nair et al., 2015; Peternell Carballo, Dooply, Leveque, Tovar, & Horkowitz, 2013).

R. Smith, (1984) once stated that, “The added cost to perform a successful primary job is much less than the cost of remedial work to repair a failure (not to mention the potential delay or loss of production).” It is for this matter therefore, substantial savings are possible with a good successful primary cement job.

Poor cement jobs are mainly due to three key factors (Chen et al., 2014; Jones & Berdine, 1940; Nair et al., 2015);

- Poor mud displacement by cements
- Improper mud cake removal during cementing operation
- Poor mixing and/or testing of cement slurry

A successful cement job is achieved by fulfilling both proper cement formulation and good displacement of both mud and mud cakes during cementing operation.

2.2.1. Poor displacement during cementing

Some of the reasons leading to poor mud displacements during primary cementing operation are:

- Eccentric annulus; when the casing is not well centralized in the wellbore, cement slurry flow more easily and faster through the wider annular gap. In the narrower gap, displacement lags behind and may be incomplete. This non-uniform annular fill-up and/or incomplete cement placement in the annulus can lead to unreliable zonal isolation (Nair et al., 2015). These abnormalities in filling up the annular space are in fact caused by high capillary pressure on the narrower side needing high pressure to displace the mud. Figure 6 shows the differences in mud heights in the annulus for both widest and narrowest sides.

  The problem of eccentric annulus is also common in horizontal wells where gravitational forces affect the centralization of casing string and promotes solids settling from the drilling fluids (Kettl, Edwards, & Covington, 1993). All these abnormalities can lead to poor mud displacement during cementing.

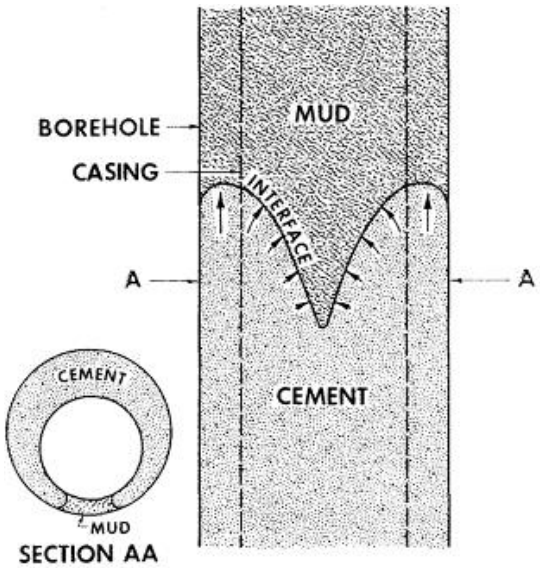

Figure 6: *Displacement of mud affected by eccentric annulus. Mud flows in the narrowest sector while cement on the widest side (McLean, Manry, & Whitaker, 1967)*

- Flow regime (pattern); turbulent cement slurry flow displaces mud better than laminar flow (McLean et al., 1967). This is due to the fact that turbulent flow produces a flat displacement profile which is good in sweeping while laminar flow produces a spearhead (distorted) displacement profile which leads to poor displacement of mud (Skalle, 2014b). Figure 7 depicts this fact.

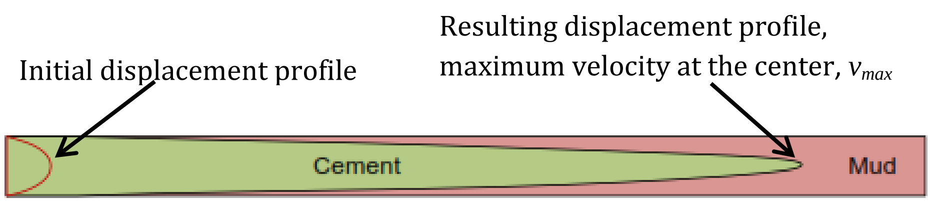

Figure 7: *Displacement profiles affected by flow regimes. For turbulent flow the displacement profile remains as the initial profile while for laminar will be distorted after a time as seen on the right (Skalle, 2014b)*

- Mud rheology; thinned or dispersed muds (Newtonian) are easily displaceable than thicker muds (Bingham fluids) (T. Smith & Ravi, 1991). For this reason it is advised to condition muds before commencement of cementing operation

Several methods and techniques have been devised by researchers and Engineers to ensure that unnecessary downtime or Non-Productive time (NPT) associated with expensive remedial actions caused by poor mud displacements are reduced or avoided. Some of the methods or techniques already developed and in use during cementing operation or production are:

- Use of centralizers to ensure casing is well centered with respect to wellbore and hence avoid non-uniform and incomplete cement placement in the annular space (Nair et al., 2015)
- Use appropriate cementing technology. Cement packer completion using Liquid Cement Premix (LCP) in off-shore Gulf of Mexico (GoM) has proved to have better results and cost saving of between 60 – 70% compared to when a normal workover rig is used (Eberhardt & Shine Jr, 2004).
- Keeping cement slurry weight at least 0.24 kg/l higher than mud and circulate cement at a very low flow rate to aid displacement process. The more eccentric the annulus, the thicker must be the cement relative to the mud (McLean et al., 1967). This helps to achieve a piston-like displacement in the annulus. In extended reach and horizontal wells, the heavier cement is even much important than in vertical wells. When a displacing fluid with higher density than the displaced fluid is used, the lighter mud in

the narrow part of the annulus will float up into the wide part and transported away with ease (Jakobsen et al., 1991)

- Condition the mud (e.g. rheology, chemistry, viscosity etc.) prior to cement pumping in the well. Thinning of mud makes it easily displaceable (McLean et al., 1967; Nair et al., 2015)
- Isolating the cement by plugs while it is pumped down the casing. This is necessary to ensure that cement reaches- and fill the whole annulus properly and also to avoid cement contamination with muds (Wilde Jr, 1930)
- Establishing turbulent flow of cement slurry in the annulus to aid good mud displacement (Howard & Clark, 1948; McLean et al., 1967).

2.2.2. Improper mud cake removal during cementing

Improper mud cake removal when running in casing string and during cementing can be caused by one or all of the following reasons which are the means of removing mud cakes properly (Jones & Berdine, 1940);

- Running in casing string without including mechanical scrapers or scratchers
- Running in casing string without applying hydraulic jetting
- Pumping in cement slurry without treating the pre-flush fluids with acids

Improper mud cake removal during well completion (cementing operation and running in casing) can be achieved by running in the casing attached with mechanical scratchers and other means of removing mud cakes like hydraulic jetting or treatment with acids and then removing them during displacement (McLean et al., 1967).

2.2.3. Poor mixing and/or testing of cement slurry

Field experiences for many years have shown that, without good cement formulation, good slurry mixing, and testing/simulating it, proper mud and mud cake displacement during cementing operation cannot yield good cement results even if the displacement is well done (Nair et al., 2015).

Good cement formulation starts at the chemistry level when cement is made at the factory. Cement mixing refers to blending/addition of other components like water, additives and/or noble gases (to make foamed cement). After cement is already prepared, it is tested in the laboratory to mimic the real conditions of the field; this is referred to as cement slurry testing. Simulation is done on special software installed on Personal Computers (PC) where the user inputs various parameters similar to the field in question. It may sometimes be done on special apparatus that simulates the actual field conditions (Haut & Crook, 1979).

2.3. Important factors for displacement during cementing

Obtaining a successful cement job for completions of both horizontal and vertical oil/gas wells is an important factor to the well's productive life (Wilson & Sabins, 1988). Successful cement job is achieved by good mud removal in the annulus (if cement slurry is well blended) which is attained through high displacement rates (T. R. Smith, 1990). To reach into a successful cement job, there are two important factors which need to be fulfilled. The factors are also relevant for estimation of displacement efficiency during cementing operation. They are (Haut & Crook, 1979; Peternell Carballo et al., 2013; Wilson & Sabins, 1988):

- Good cement job design
- Good understanding of displacement mechanics

Before explaining these two factors, a definition of cement displacement efficiency is given first. The *displacement efficiency* during cementing is defined as the ratio of cement volume that is pumped into well to the total annular volume that is to be cemented, see equation (1). Similarly, if a well cross-section is considered as seen in Figure 8, then the displacement efficiency can be defined as the ratio of cemented area to the total annular area as summarized by equation (2) (T. R. Smith, 1990; Wilson & Sabins, 1988).

Mathematically, displacement efficiency, ε is written as;

$$\varepsilon = \frac{Pumped\ cement\ volume}{Total\ annular\ volume} \tag{1}$$

$$\varepsilon = \frac{Cemented\ Area}{Annular\ Area} \tag{2}$$

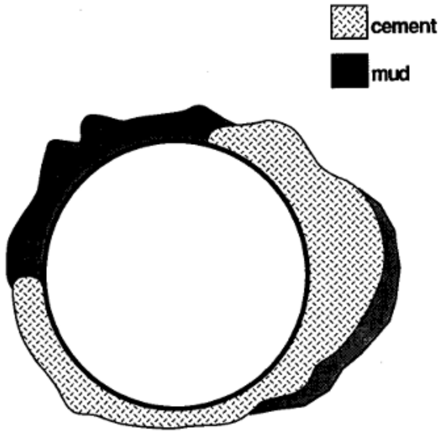

Figure 8: *Cross-section of a cemented annulus defining displacement efficiency of equation (2) (T. R. Smith, 1990)*

To attain a successful cement job, displacement efficiency should be higher than 100%, that is, the pumped cement volume should be higher than the total annular volume to be cemented; otherwise, it will result into poor displacement job as seen in Figure 8 or lower top of cement (TOC) than planned.

In highly deviated and horizontal well conditions, achieving high mud-displacement efficiency requires additional special attention be given to two aspects of drilling and/or completion practice. This is necessary in order to obtain optimum mud displacement and cementing results. The two aspects are (Wilson & Sabins, 1988):

- Drill-fluid systems and properties
- Casing and hole sizes

The drilling fluid has large impact on wellbore stability since it leads to swelling formation due to complex interaction between water based muds (WBM) and shales. It can also lead to under-gauged hole for mobile formations or hole collapse if too low mud weights are used (Martins, Santana, Campos, & Gaspari, 1999). Similarly, for casing and hole sizes, if annular space is small it will automatically complicate the displacement process as described under chapter 2.2.1.

Generally, both two aspects will have negative impacts on displacement efficiency during cementing.

2.3.1. Good cement job design

Majority of the remaining hydrocarbons in the world are located on the continental shelves (Skalle, Aamodt, & Gundersen, 2013b). To maximize production potential and reduce development costs of these fields, horizontal wells present an effective method (Kettl et al., 1993). Since the number of complex wells being drilled today to reach these fields, especially in deep waters and other challenging environments (high temperature high pressure (HTHP), extended reach drilling (ERD), shallow gases and salt domes) is increasing, the possibility of constructing wells that deviate from the original well plan also becomes high. To encounter these deviations from the original well plans, application of systematic and integrated approach to well construction process that meet new industry and regulatory requirements has to be increased (Peternell Carballo et al., 2013).

Most of the today's cement job designs are done on computers to simplify the job design and simulate the real cementing environments. This has become popular, especially, after the invention of Graphical user Interfaces (GUI) ran on Windows based PC's (Kulakofsky, Henry, & Porter, 1993). The software installed on these PC's are used in calculations of hole volume, cement slurry volume, density, viscosity and simulate mud displacement for cementing (Peternell Carballo et al., 2013; Torsvoll, Olaussen, & Almond, 1991). In this work, focus is made to hole and cement slurry volumes estimation.

Determination of the total volume of cement slurry required for the job is the first step in preparing for primary cementing job. The required slurry volume is calculated by computing the casing-to-hole annular volume (Mian, 1992). Good cement slurry formulation/mixing, testing and displacement during pumping in the annulus can be well performed, but if insufficiently filled the annulus; it leads to low top of cement (TOC) as anticipated. Insufficient annular fill-up (especially TOC) is caused by poor cement slurry volume calculation to match the annular spaces. Different methods have been developed to calculate hole volume and hence estimation of slurry volume. These techniques are:

1) *Estimation of slurry volume from caliper measurements* (Peternell Carballo et al., 2013).

   The requirements for determining hole volume for wells drilled with water based mud (WBM) in deep-water environments can be met using the existing Logging While Drilling (LWD) electro-magnetic propagation resistivity measurements. The hole size leading to determination of hole volume is obtained from caliper measurements (specific LWD caliper inversion processing in this method). Cement slurry volume can then be estimated based on the hole size determined by either excess percentage (150 – 200% of hole size) or fluid caliper values. This method is applicable in riser-less top hole sections especially in off-shore GoM. The caliper measurements in this method are affected by big uncertainty of mud resistivity. The technique to overcome this uncertainty is by implementing a simultaneous inversion model and forward modeling database from standard 2-Mhz propagation resistivity for water-based mud (WBM) and large boreholes (top hole sections) (Peternell Carballo et al., 2013).

In order to attain high accuracy in estimation of hole size and shape, the caliper tool used in this technique should be able to record the greater numbers of independent measurements (four-pad two axis measurements or six-pad independent measurements caliper). In case Wireline calipers are not available, an estimation of hole size can then be done by either specifying a given percentage of excess of the bit size or having “Fluid Caliper” with tracer materials to detect the returns at sea floor (Peternell Carballo et al., 2013).

Furthermore, this technique can advance the Measurements While Drilling (MWD) and LWD tools to enable estimation of open hole size from acoustic and nuclear measurements or resistivity measurements in conductive drilling muds (Peternell Carballo et al., 2013). This advancement adds value to this method in determining hole volume compared to other methods that depend on only one means for determining the volume.

2) *Cement slurry volume (V_{cs}) estimated from wellbore geometrical model* (Amanullah & Banik, 1987).

Calculation of slurry volume in this method is based on a wellbore with circular geometrical shape. Slurry volume is obtained using a formula as seen in equation (3) and shown principally by Figure 9. The main assumption in this method is that, since the open hole length is large, the inside diameter of previous casing is also assumed to be equal to mean diameter of the open hole. The equation is modeled (developed) by integrating $V = f(h)$ for a constant wellbore and casing diameter and dividing the horizontal plane into n equal triangles (Figure 10) and the total depth into m equal intervals (Amanullah & Banik, 1987).

$$V_{cs} = \frac{\pi}{4} k(D_m^2 - D^2)L_c + d^2 h_c \qquad (3)$$

Please see nomenclature for definition of parameters.

The accuracy of this method is largely affected by the process of determination of wellbore mean diameter D_m. The bigger the number of triangles n, the higher the accuracy of the geometrical mean diameter D_m. Another constraint to this method is that, the annular volume grows considerably as the wellbore becomes more irregular and consequently a detailed study of the wellbore configuration is essential in order to minimize the volume fluctuation from the actual (Amanullah & Banik, 1987). To be more precise the method is modeled on PC using application software like Matlab or similar software.

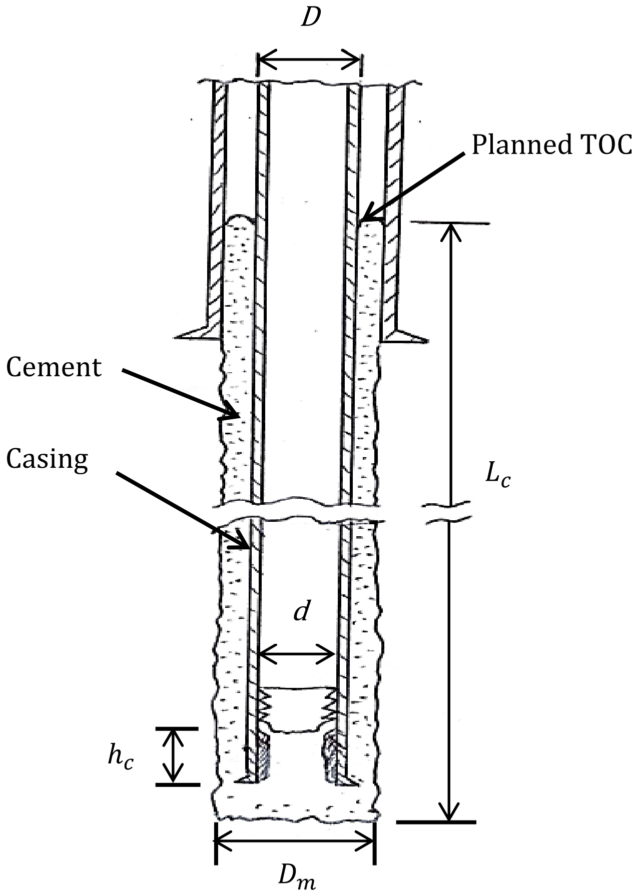

Figure 9: *Principal sketch describing parameters in equation (3)*

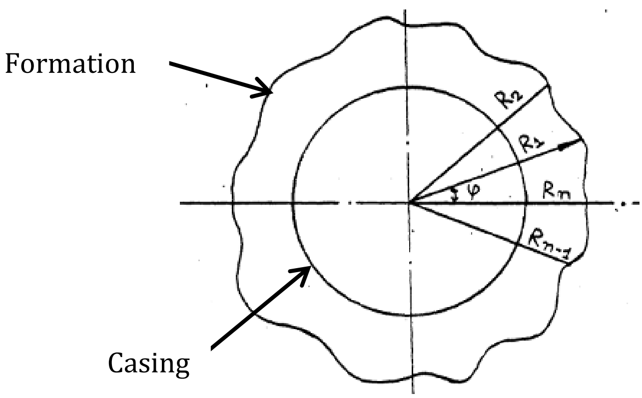

Figure 10: *Principal sketch describing estimation of mean diameter, D_m in equation (3)(Amanullah & Banik, 1987)*

3) *Cement slurry volume obtained from average hole diameter,* d_{av} (Mian, 1992).

Most drilled holes are exposed to washouts, ledges, caves and tight holes. Determination of cement slurry requirement for these holes is done by first calculating the average hole diameter and then use it to obtain annular volume. Determination of average hole diameter, d_{av} is achieved by using equation (4) and is described principally by the exaggerated wellbore in Figure 11. This method is somehow similar to method 2) presented by equation (3) since it is also based on determination of the average diameter. The difference is how this average/mean diameter is being estimated. The approach in this method is that the well is divided into j vertical sections of equal length L (Mian, 1992) whereas in method 2) the horizontal plane is divided into n equal sectors.

$$d_{av} = \sqrt{\frac{1}{L_t}\left(d_1^2 L_1 + d_2^2 L_2 + \cdots + d_j^2 L_j\right)} \qquad (4)$$

Please see nomenclature for definition of parameters.

The slurry volume is then determined using equation (3) but the mean diameter, D_m in equation (3) is replaced with average diameter, d_{av}. The bigger the number of vertical sections j, the higher the accuracy of the d_{av} and hence is the total volume of slurry. To achieve high accuracy (using big number of sections), equation (4) is modeled on PC application software like Matlab or similar software.

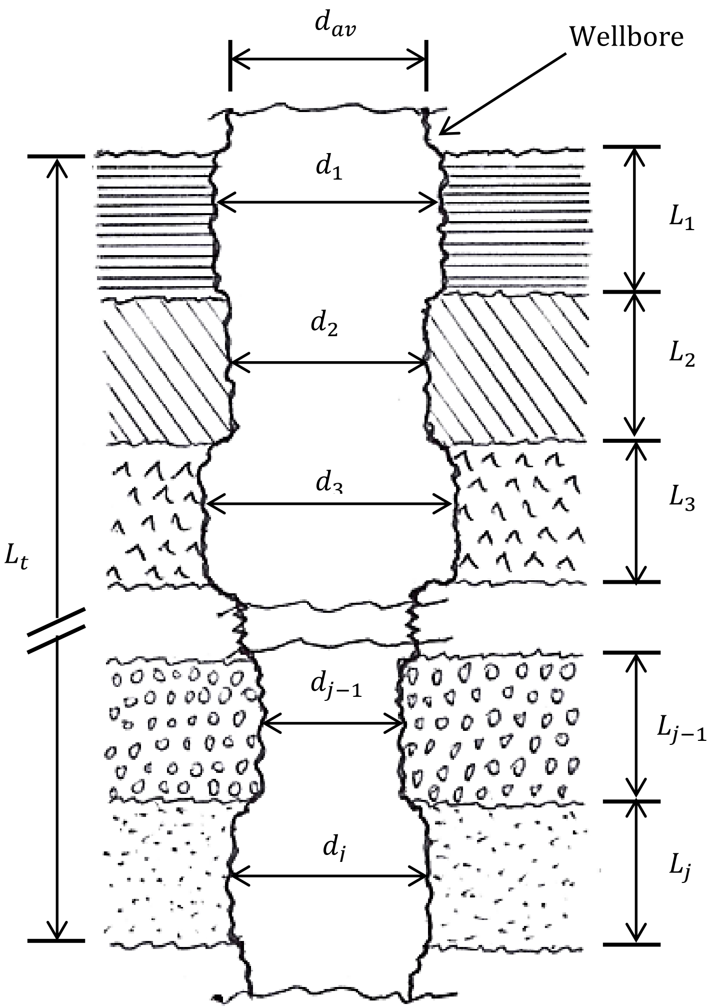

Figure 11: *Principal sketch for estimating wellbore average diameter, d_{av} by equation (4)*

2.3.2. Good understanding of displacement mechanics

Successful cement job depends much on good and sufficient displacement during cementing. According to various research work on displacement mechanics, six basic factors were found to have influence on displacement for both vertical and horizontal wells (Haut & Crook, 1979;

Jakobsen et al., 1991; Kettl et al., 1993; T. Smith & Ravi, 1991). The factors are:

- Condition of the drilling fluid (Mud rheology)
- Pipe movement
- Type of fluid flow (regime)
- Pipe centralization (eccentric annulus)
- Difference in densities between displacing and displaced fluids
- Amount of fluids flowed past a particular interval

Mud rheology has influence on displacement process in two ways. When mud is conditioned to have less viscosity it will be displaced easily and hence high displacement efficiency (Haut & Crook, 1979; T. Smith & Ravi, 1991). On the other way, when gel strength of mud is increased, the difficultness of being displaced is also increased and hence lowering displacement efficiency (Haut & Crook, 1979; McLean et al., 1967).

Pipe movement is another important factor for good displacement during cementing. According to McLean et al., (1967), there are two types of pipe movements namely; rotation and reciprocation. The rotation movement is more beneficial especially when the casing is severely off center since the drag forces tend to pull cement into by-passed mud. On the other hand, reciprocation is required to pull water into the mud column, making both types of pipe movements important for the displacement process (Haut & Crook, 1979; McLean et al., 1967).

There are basically three types of flow regimes in displacement process namely; plug flow, turbulent flow and laminar flow discussed under chapter 3. According to McLean et al., (1967), thinned muds are easily displaced by turbulent flow (high flow rates) of cements in vertical wellbores for well centered casings. However, for the case of horizontal and deviated wellbores (or eccentric annulus in vertical wellbores) turbulent flow will lead to bypassed muds on the narrower sides due development of distorted displacement profile as seen in Figure 7. Pipe eccentricity in horizontal and deviated wells is caused by pipe weight. In this case laminar flow of cement slurry with cement having higher density than muds will lead to good displacement (Kettl et al., 1993).

Well centered pipe will lead to efficient displacement. If the pipe is eccentric mud will tend to flow on the wider side thereby bypassing muds in the narrower sides due to pressure drop in the annulus hence poor displacement efficiency (Haut & Crook, 1979; Jones & Berdine, 1940).

The effect of gravity forces due to differences in densities of displaced and displacing fluids has influence on displacement process. If the displacing fluid (cement) has higher density compared to muds, it will aid in breaking the gel strength of muds and hence good displacement (Haut & Crook, 1979; McLean et al., 1967). Density difference has great benefits in displacements of horizontal and highly deviated wellbores.

According to Brice & Holmes (1964), their field study concluded that pumping displacing fluid past a specific interval in the annulus for more than 10 minutes in turbulent flow regime will result into a successful cement job due to good displacement (Haut & Crook, 1979).

2.4. Requirements and Standards for a successful cement job

The requirements for good displacements and hence successful cementing jobs are as described under chapters 2.2 and 2.3.

Jakobsen et al., (1991), conducted an experimental work using a 60º large scale deviated apparatus simulating a deviated wellbore which proved that when a displacing fluid has higher density than the displaced fluid by 5%, the latter fluid floated up in the wider annular space due to buoyancy and was therefore transported with ease leading to efficient displacement.

Similarly their experimental work went on further to determine the effect of viscosity differences between displaced and displacing fluid. It was concluded that as the viscosity of mud (displaced fluid) becomes lower than that of cement (displacing fluid), a better displacement was achieved. This agrees with the study by T. Smith & Ravi, (1991) that says thinned (low viscosity) muds are more easily displaceable than non-dispersed muds.

Failure to adhere to the cementing standards will obviously lead to failure of cement jobs. Standards help to control such factors as casing designs, cement slurry designs (density, viscosity, additives etc), and the entire displacement process. Loss of control of one of the mentioned factors can lead to adverse consequences like (O'Neill & Tellez, 1990):

- Poor cement bonding with either casing or formation or both
- Incomplete annular fill-up by cements during cementing leading to poor displacement efficiency
- Lower compressive strength of the set cement

- Inefficiency of cementing additives
- Erroneous cement slurry thickening time
- Possibility of inability to control formation pressure especially if slurry density control is lost.

3. Theoretical Considerations of Cement jobs

Mud displacement is a complex process in completion phase of oil wells especially in deviated and horizontal wells that necessitate good designs of both well and cement job. This chapter describes the factors relating to fluid flow regimes and cement tops that affect displacement efficiency and how efficiency is determined. Displacement efficiency can be found theoretically (during planning phase) or practically after the cement job. The chapter also gives the significance of both planned and practical displacement efficiencies in assessing cement job quality.

3.1. Flow Regimes during Cement Displacement

For any flowing fluid, the velocity distribution is dictated by the type of flow regime in a pipe (Lupyana, 2015). There are three types of flow regimes in any type of fluid. These flow regimes are also applicable in cement slurry during displacement in the annulus. The known flow regimes are (Renpu, 2011):

- Laminar flow
- Plug flow
- Turbulent flow

The type of flow regime is determined by a dimensionless quantity called Reynolds Number, N_{Re} given by equation (5), (Skalle, 2014a)

$$N_{Re} = \frac{\rho v_m d_{pipe}}{\mu} \qquad (5)$$

The values of N_{Re} determining each flow regime for different pipe wall roughness are as summarized in Table 2.

Table 2: Reynolds numbers N_{Re} for different flow regimes and wall roughness (Skalle, 2014a)

Flow Regime	**N_{Re} for non-slick pipe walls**	**N_{Re} for Slick pipe walls**
Laminar flow	$0 < N_{Re} < 1800$	$0 < N_{Re} < 1800$
Transition flow	$1800 < N_{Re} < 2100$	$1800 < N_{Re} < 3000$
Turbulent flow	$N_{Re} > 2100$	$N_{Re} > 3000$

3.1.1. Laminar flow

For fully developed laminar flow the velocity distribution at any radius *r* is given by Navier-Stokes equation (6). This equation (6) shows that the velocity profile is paraboloid and the axial velocity is high near the center of the annulus than near the walls. The maximum velocity v_{max} at the center where $r = 0$ is given by equation (7) (Lupyana, 2015; Skalle, 2014a). Figure 12 shows the laminar velocity profile of cement in the annulus.

$$v = -\frac{1}{4\mu}\frac{dp}{dx}(R^2 - r^2) \tag{6}$$

$$v_{max} = -\frac{1}{4\mu}\frac{dp}{dx}R^2 \tag{7}$$

As seen in Figure 12, the spearhead profile of laminar flow has a negative impact on cement displacement since the displacing fluid (cement) penetrates in the center of mud and so leaving some of the mud/spacer around the walls. This causes poor cement bonding with either casing or formation or both.

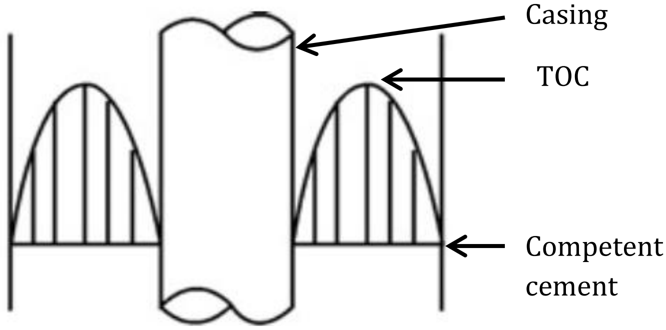

Figure 12: Laminar flow causes distorted velocity profile of cement slurry in the annulus (Renpu, 2011)

3.1.2. Plug flow

This flow regime has a gentle (almost flat) velocity distribution profile as seen in Figure 13. This type of flow velocity favors a uniform advancing of cement slurry to displace mud in the annulus (Lupyana, 2015). No distortion of velocity profile.

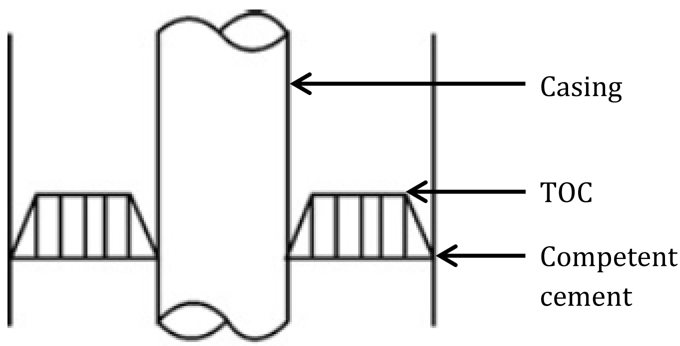

Figure 13: Plug flow velocity profile of cement slurry in the annulus (Renpu, 2011)

3.1.3. Turbulent flow

When the Reynolds Number N_{Re} increases past its transition region the flow turns from laminar to turbulent. Turbulent flow is a chaotic flow in which the velocity of fluid particles varies continuously in an irregular manner leading to high friction losses along the walls and producing a non-distorted velocity profile (Lupyana, 2015; Skalle, 2014a). Figure 14 illustrates the flat velocity distribution of turbulent flow regime.

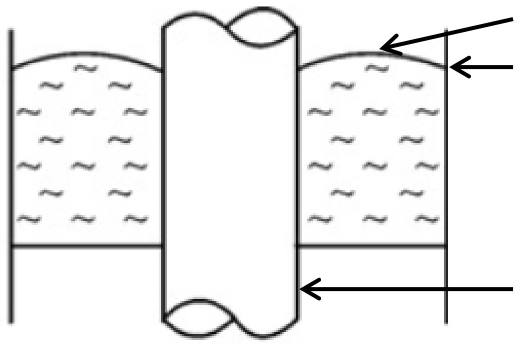

Figure 14: Turbulent flow regime produces an almost flat velocity profile of cement slurry in the annulus (Renpu, 2011)

3.2. Cement Tops

In this thesis work, it was assumed that there are two important types of cement tops in cementing operations in which either of the two can appear during or after cement displacement. The tops are:

- Top of cement (TOC): This is the extreme point (highest height) reached by a good cement in the annulus. When measured from surface is referred as depth in MD or TVD.
- Top of competent cement: This is the highest height reached by the quality cement bonding with both casing and formation.

The two tops are affected differently depending on the stage (status) of the cement job in question. During cement displacement operation the two types of cement tops are determined by cement displacement profile (flow regime) and viscosity or density of slurry as discussed under Chapter 3.1. On the other hand, after the cement job, these two cement tops are affected by viscosity and density of slurry.

As a matter of fact, after the cement is displaced and settled in the annulus, viscous and dense cements (with good sweeping ability) are expected to have a tendency to raise the top of competent cement but retain TOC developed during displacement. Cements with less viscosity and density (less sweeping ability) will have a tendency to lower (flatten) the TOC but retain their top of competent cement. Figure 15 shows how heavy and light cements behave after settling in the annulus. Both are assumed to be displaced in laminar flow.

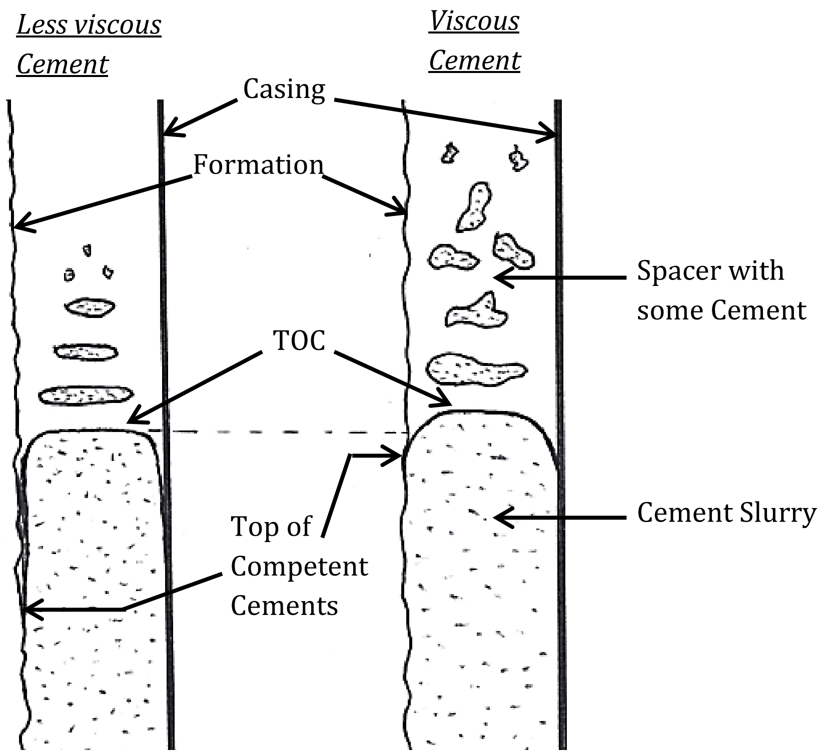

Figure 15: Assumed cement tops exhibited by viscous and less viscous cements after settling in the annulus (Equal theoretical and pumped cement volumes)

3.3. Definition of Cement Displacement Efficiency

Generally, displacement efficiency is the parameter used to describe the ability of one fluid to displace another fluid (Lupyana, 2015). Cement displacement efficiency is the ratio used to express the ability of cement slurry to displace mud during cementing. The general definition of displacement efficiency is seen in equation (8). The displacement efficiency (ratio) is also a factor used to assess quality of the cement job.

$$Displacement\ ratio = \frac{Volume\ of\ displacing\ fluid}{Volume\ of\ displaced\ fluid} \quad (8)$$

As stated earlier in this chapter 3, cement displacement efficiency can be determined in two ways:

- Pre-determined before the cement job. This gives the planned or theoretical displacement efficiency $\varepsilon_{theoretical}$
- Determined after the cementing operation which gives actual or practical cement displacement efficiency $\varepsilon_{practical}$

Both types of displacement efficiencies are affected by flow regimes of cement slurry in the annulus.

3.3.1. Determination of Cement Displacement ratio theoretically

Cement displacement ratio $\varepsilon_{theoretical}$ obtained in this method is called *theoretical* or *planned* displacement efficiency. It is dictated by two physical quantities namely; theoretical volume ($V_{theoretical}$) and pumped volume (V_{cement}). That is, the ratio of V_{cement} to the $V_{theoretical}$.

Assuming cement is displaced in turbulence, then the difference in height/ top of cement (TOC) and height/top of competent cement is small (see Figure 14). This leads to a slight discrepancy in estimation of $V_{theoretical}$. In order to get the theoretical displacement efficiency right, $V_{theoretical}$ had to be correctly estimated.

Theoretical volume, $V_{theoretical}$ (or calculated volume) to be cemented is the volume of the annulus from the rat hole to where the theoretical TOC is anticipated. The pumped volume, V_{cement} is the volume that is pumped into the well. In order to achieve good displacement, V_{cement} must be higher than the $V_{theoretical}$. The cement displacement ratio is given by equation (9).

$$\varepsilon_{theoretical} = \frac{V_{cement}}{V_{theoretical}} \quad (9)$$

Theoretical cement displacement ratio must be greater than unit for a good and successful cement job.

Correct estimation of $V_{theoretical}$ results in good both displacement and actual TOC close to plan. In principal the total $V_{theoretical}$ is made up by the summation of four components as seen in equation (10) and depicted in Figure 16. The involved components are:

- Annular volume between current casing and previous casing. That is, the casing overlap
  $= \frac{\pi}{4}(D_i^2 - D^2)L_1$
- Annular volume between open hole and current casing.
  $= \frac{\pi}{4}(D_m^2 - D^2)L_2$
- Volume of space from thrust collar to the casing shoe (shoe track)
  $= \frac{\pi}{4} d^2 h_c$
- Volume of space below current casing shoe (hole sump/rate hole)
  $= \frac{\pi}{4} D_m^2 L_R$

Therefore, the total theoretical volume is found by equation (10)

$$V_{theoretical} = \frac{\pi}{4}[(D_i^2 - D^2)L_1 + (D_m^2 - D^2)L_2 + d^2 h_c + D_m^2 L_R] \quad (10)$$

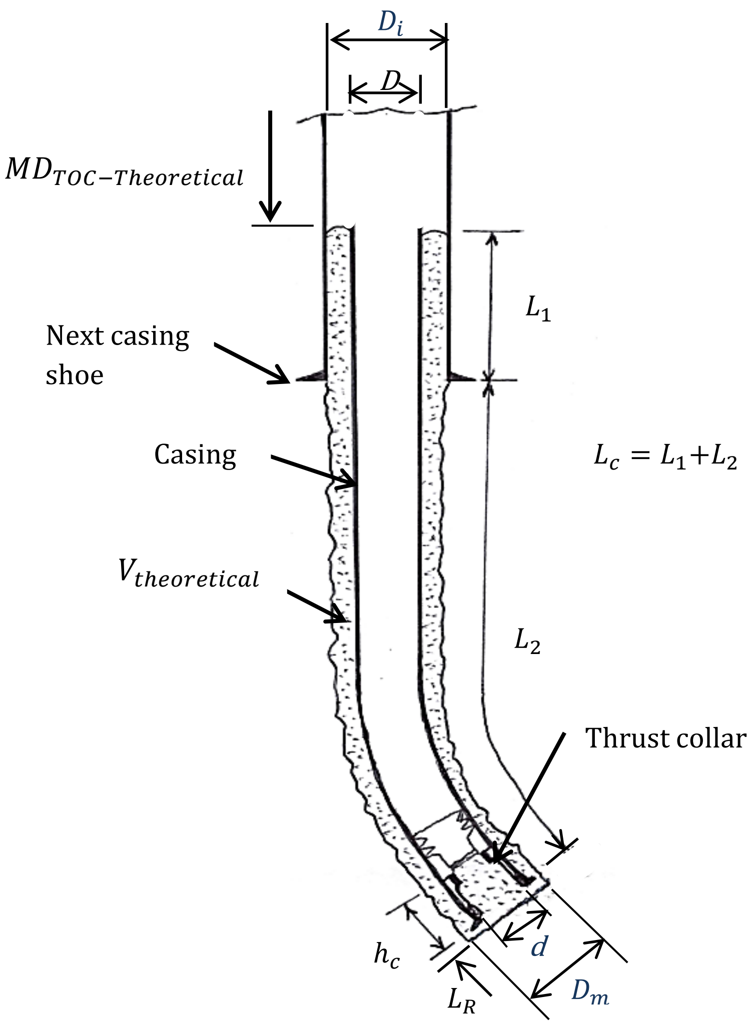

Figure 16: *Sketch showing components of Theoretical Volume for determination of theoretical displacement efficiency (ratio)*

3.3.2. Determination of Practical Cement Displacement Efficiency

The efficiency found in this method is the actual one. It is found after the cement is already pumped and set in the annulus. The actual cement displacement efficiency $\varepsilon_{practical}$ depends on CBL log data like TOC and is defined in equation (11).

$$\varepsilon_{practical} = \frac{TOC_{observed}}{TOC_{theoretical}} \qquad (11)$$

For good cement job, the ratio $\varepsilon_{practical}$ must be equal to or greater than one. Assuming flat displacement profile of cement in the annulus, the theoretical TOC is taken equal to planned height of competent cement in the annulus. Figure 17 shows an insufficiently displaced cement job indicated by observed TOC being less than theoretical TOC.

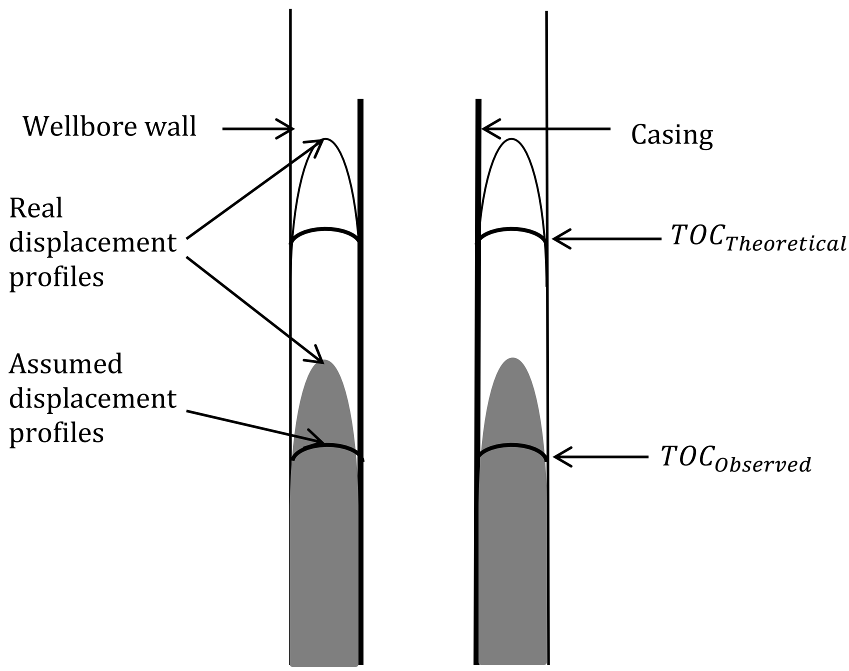

***Figure 17**: Cross-section of a cemented well showing Low observed TOC indicating an insufficiently displaced cement job*

4. Ontology engineering of the cementing process

4.1. Definition and Importance of Ontology Engineering

Once a failure has occurred, it is important to know the exact root cause and take counter measures to cure the problem and if possible to take also preventive measures in order to avoid problem reoccurrences.

Ontology engineering is used to study concepts that are used to convey the flow of failure causes (symptoms) and their relationships in order to establish the exact root cause(s) of the failure in oil wells construction operations (Skalle, Aamodt, & Gundersen, 2013a). Ontology engineering is also used to ease communication of technical information regarding failures of cement jobs between drilling- and completion engineers and researchers.

The motivation behind this chapter is that, there are many causes of failures in cement jobs (discussed in chapter 2 and further in chapter 4.2). Many cases of failed cement jobs are hard to establish what their exact causes are. This is because there are many symptoms of failures in cement jobs as seen in Table 6 (Failure Ontology Template).

Ontology engineering was helpful to pin-point the exact root cause(s) for each failure case which was accomplished through two tools:

- Preparation of causal relation for each failure case. In building causal relations, assumptions of the used path strengths for different relations are presented in Table 3. They are grouped in only five steps (strengths) to simplify building of causal relations for ontology engineering of cases. Explanation strength is obtained by adding all the path strengths in the particular target error

- Building one subclass model of the involved symptoms versus all potential failures during or after cementing. The subclass model is presented in Figure 18.

Table 3: Assumed causal relations with their respective path strengths

Relation	Assumed path strength
Causes always	1.0
Leads to	0.8
Causes sometimes	0.6
Causes occasionally	0.4
Rarely leads to	0.2

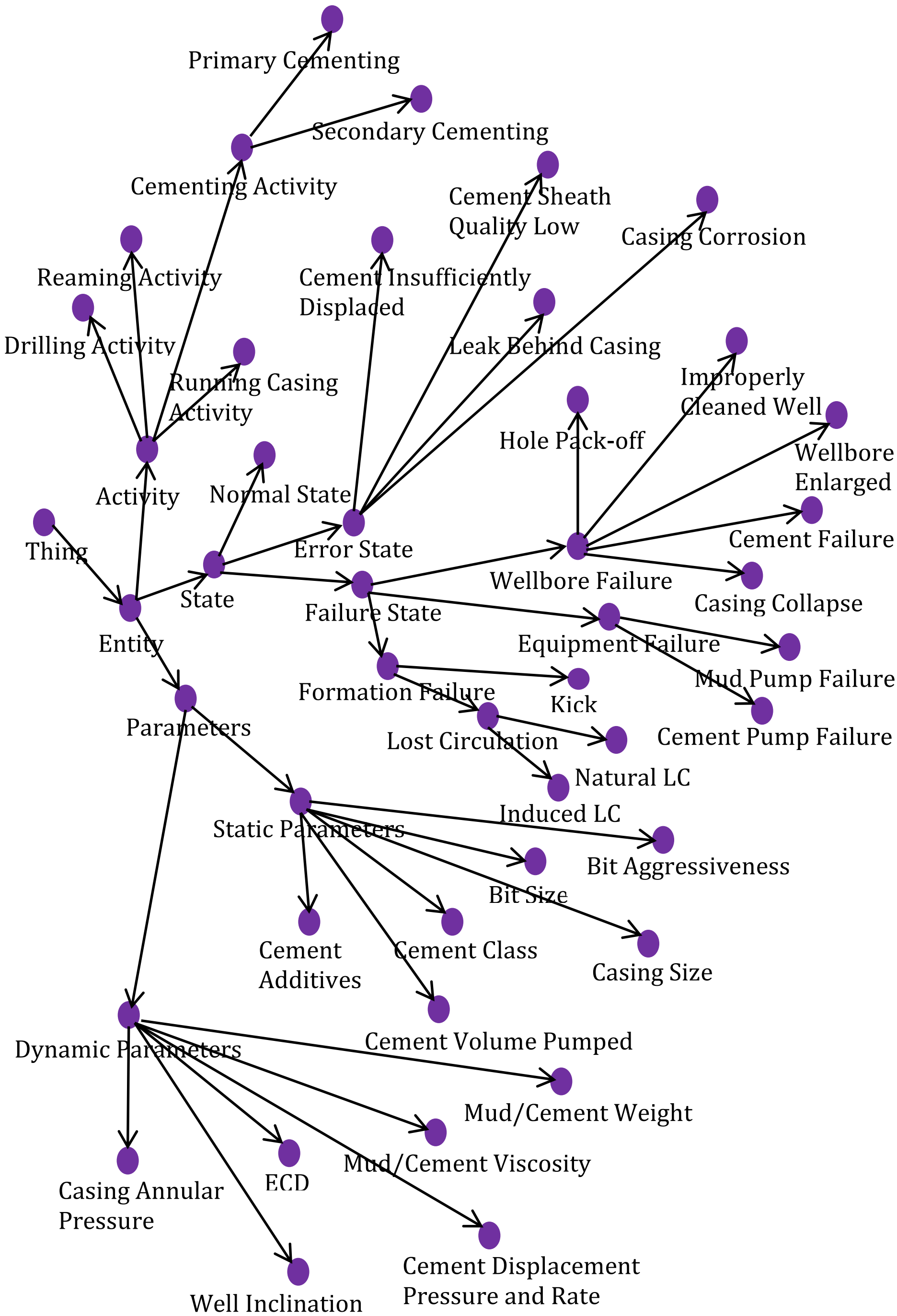

***Figure 18**: Subclass Model for all Failure Cases*

4.2. Causes of cement job failures (in detail)

As discussed under chapters 2.2 and 2.3, proper mud displacement during cementing is crucial to well completion. When cement is pumped and displaces mud in laminar flow rate, the slip velocity on the walls leads to a high velocity at the center, v_{max}. The maximum velocity v_{max} will make cement penetrate at the center of mud leading to distorted displacement profile as seen in Figure 7. Other cementing challenges that lead to poor cement jobs related to displacements, wellbore geometry, and formations are presented in Figure 19 and Figure 20 and supplemented by Table 7.

In build-up sections, the number of casing centralizers may sometimes be limited due to complexity of well design and pipe drag forces. This limitation leads to casing pipe being decentralized (narrow annulus or even get contacted with formation at the top side) due to high pipe bending resistance and few installed centralizers. Figure 19 depicts this fact. Similarly, in drop-down sections, the pipe will be in contact with the formation at the bottom side due to two reasons; pipe bending resistance and pipe weight. Decentralization of casing causes uneven pressure differential in the annulus which in turn leads to uneven flow of cement slurry. The result is a much difference in TOC on the narrow and wide sides of the annulus (Pks, Savery, & Morgan, 2010). That is, the TOC is high on the wide side and low on the narrow side as seen in Figure 19.

Figure 19 and Figure 20 show how challenging a cement job is especially if theoretical volume is wrongly estimated (lead to poor displacement). Figure 19 shows differences in actual TOC for wide and narrow annuli. It is high in the wide annulus and low in the narrow annulus. But also the actual TOC is below the anticipated (planned) TOC for both wide and narrow annuli which may lead to requirement of a squeeze cementing. The actual TOC is commonly obtained from CBL logs or similar tools.

Ledges are also another cause of poor displacement during cementing. They lead to poor cement bond especially with the formation because they block a continuous flow of cement in the annulus. If the ledge is long enough to touch the casing string, the effect is even worse since cement will then not bond with both the casing and formation as seen on the narrow side of casing annulus in Figure 19.

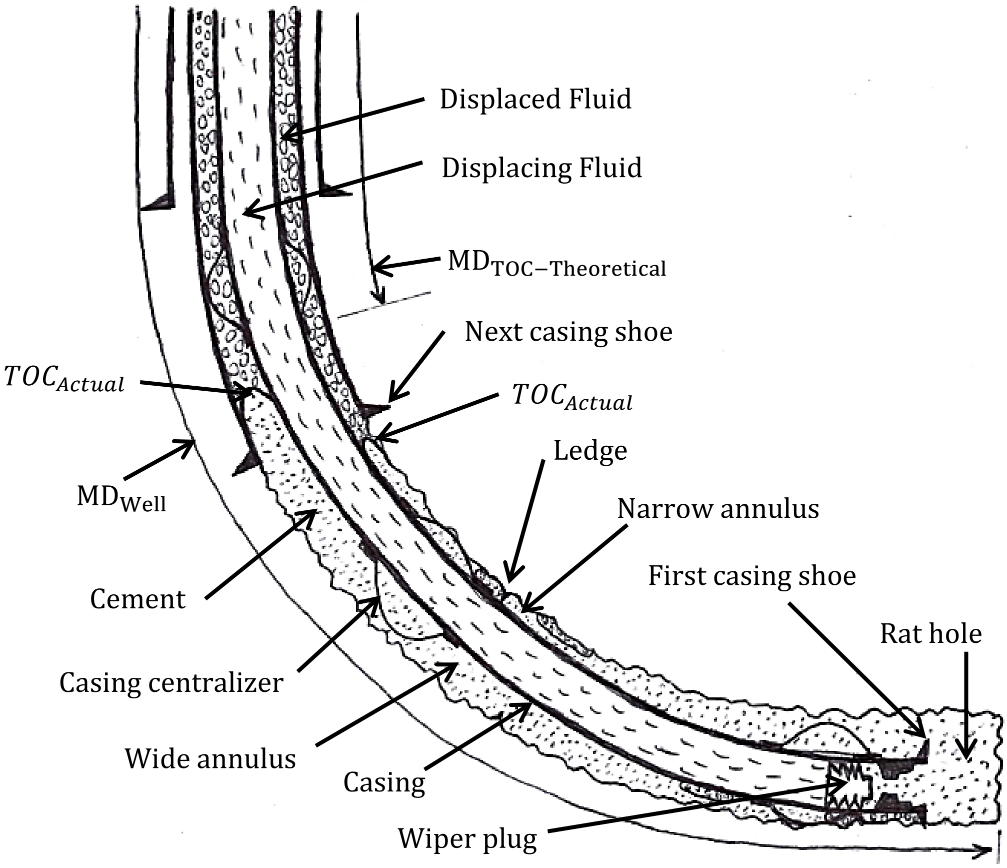

Figure 19: *Sketch defining displacement challenges and possible causes of cement job failures during cementing operation*

Figure 20 shows poor cement job which is caused by poor displacement during cementing. The cement has not bonded properly to both casing and formation on the narrow side and it is also gas-cut (compromised) on the wide annulus. Channels in cements and poor bonds hold muds or spacer fluid in them. Basing on definition of displacement efficiency by equation (2), Figure 20 represents poor displacement efficiency of the cement job.

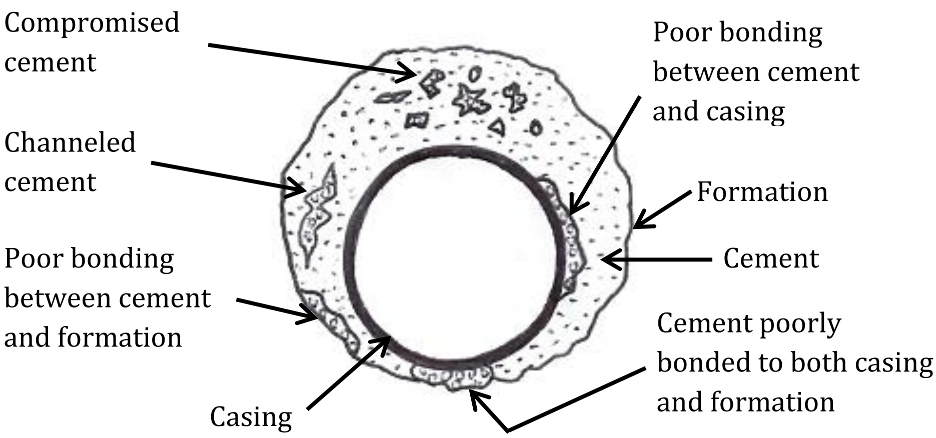

Figure 20: Cross-section of cemented well showing various cementing problems related to displacement (Cameron, 2013)

5. Cases of poor cement jobs

In order to clearly understand cases with unsuccessful annular filling with cement and use them as evidences of poor cement displacement jobs, the presented cases are subdivided into two groups, A and B:

- Group A presents cases of normal cement jobs. In these cases, the point is to check the cement displacement efficiency independent of success level. Some good cases were also pointed at without checking their displacement efficiency, only cementing failure in general, that is, cases for the purpose of failure evaluation through Case Based Reasoning (CBR).
- Group B presents cases of failed cement jobs. These are cases in which cement has failed filling the annulus properly. Cement Job quality is checked at times before- (planned displacement, Theoretical TOC), during-, and after the cement job (CBL results like observed TOC, cement bond etc)

5.1. The raw data

This chapter is intended to introduce the reader to the different input data used in analysis of both normal and failed cases of cement jobs. Inputs include static data which are known before the cementing operation starts, and the collective data which are measured after the job. Available drilling and/or cementing parameters (raw data) together with the purpose (motivation) of each parameter are summarized in Table 4. Each input parameter has its importance in analysis of cases. It is needed either for determination of displacement efficiency (ε) or for analysis of failure ontology or both.

Quantities estimated from the raw data (Theoretical volume, Theoretical displacement ratio, Actual displacement efficiency, Cement volume derived from CBL or similar tools, Lost cement volume, and Fraction of pumped volume that has actually filled the annulus) are shown in Table 5 (Case Template).

Table 4: Raw data (inputs) used in analysis of both normal and failed cases for the time before-, during- and after the cement job. The essence of each input data is stated in the last column (whether needed for determination of displacement efficiency (ε) or for failure ontology or both)

Time	Drilling/Cementing Parameter	Description/Options	Parameter needed for
Before displacing cement	Bit size	Previous section	ε
	Bit size	Present section	ε and Failure ontology
	ID.Csg	Previous csg	ε
	ID.Csg	Present csg	ε
	OD.Csg	Present csg	ε and Failure ontology
	MD.Csg shoe	Previous csg	ε
	MD.Csg shoe	Present csg	ε
	MD.Float colar	Present csg	ε
	MD.Top.csg/liner	Present csg/liner	ε
	MD.Build/Drop.Upper	Its approximate mid-point. Upper is normally inside csg	Failure ontology
	MD.Build/Drop. Lowest	Its approximate mid-point. Could well be in the openhole. If only one build/drop then upper is also the lowest!	Failure ontology
	Fm Special Expected	2 options: Yes or No --> Yes; (to be stated what special)	Failure ontology
	Fm Fault Expected	2 options: Yes or No --> Yes; could lead cement loss	Failure ontology
	Losses Expected	2 options: Yes or No --> Yes; in Tare	Failure ontology
	MD.Well	Well TD	ε and Failure ontology
	TVD.Well	True Vertical Depth for deviated wells	ε and Failure ontology
	MD.Plug	Plugged TD (if well is plugged back)	ε
	Length.csg/cement. overlap (L1)	Planned Length into previous csg	ε
	Length.openhole (L2)	Length of Open hole interval	ε and Failure ontology
	Length.cement (Lc)	Length of the cementing interval (L1+L2)	ε and Failure ontology
	Length.rat.hole (LR)	Length of Rat hole	ε and Failure ontology
	Mean.dia (Dm)	Wellbore mean diameter (open hole)	ε and Failure ontology
	Length.shoe.track (hc)	Distance from thrust collar to csg shoe	ε and Failure ontology
	Well inclination	Average angle of the last hundreds metres	Failure ontology
During displacing	Cement Loss	Lost rate to the formation (% of pump rate)	Failure ontology

cement	Frac D – ECD	Narrow pressure margin during cement displacement	Failure ontology
	Well Packed-off	2 Options: Yes or No → Yes; leads to cement loss	Failure ontology
	Pressure Bleeding High	Pressure drop rate during pressure testing is high	Failure ontology
After displacing cement	MD.TOC	Theoretical	ε and Failure ontology
	MD.TOC	From CBL or similar tools (Actual)	ε
	Theoretical TOC	Planned Height of cement in annulus referred from MD.Well	ε
	Observed TOC	Actual Height of cement derived from CBL or similar tool	ε
	V.Cement (V1)	The pumped volume	ε and Failure ontology

5.2. Reporting structure

This chapter gives explanation of the points and formats used to analyze both normal and failed cases of cement jobs. Normal jobs (where displacement efficiency was checked) are analyzed using Case Template presented in Table 5. Ontology engineering and causal relations were not carried out for normal jobs. The failed cases were analyzed using two more Templates named; “Failure Ontology Template” and “Causal relations Template” which are presented in Table 7 and Table 8 respectively.

For normal jobs where only displacement efficiency is of interest Table 5 bears two parts as follows:

- *Raw data*. This part is filled with the available input parameters needed for determination of displacement efficiency. Probability in this section shows how close to the actual values are the quantities of guessed or assumed value of a parameter. 100% probability means the quantity is not assumed or guessed; rather it is an exact value.

- *Calculated (Estimated) results*. Quantities calculated from the raw data (inputs) are:
  i) Theoretical Volume (V2)
  ii) Theoretical displacement ratio. Ratio of pumped cement volume to Theoretical volume (V1/V2)
  iii) Actual displacement efficiency obtained as the ratio of observed TOC to theoretical TOC
  iv) Cement volume derived from CBL logs or similar tools (V3)
  v) Cement volume that has lost to formation during pumping (V4). It is known after CBL run
  vi) Fraction of pumped volume that has actually filled the annulus (V3/V1)

Table 5: Case Template presenting data related to Displacement Efficiency

Well Name and Section:					
Data Source:					
1. *Raw data*					
Available drilling/Cementing Parameter	**Description**	**OFU**		**SI**	**Probability**
		Quantity	Unit	Quantity	
Bit size	Previous section				
Bit size	Present section				
ID.Csg	Previous csg				
ID.Csg	Present csg				
OD.Csg	Present csg				
MD.Csg shoe	Previous csg				
MD.Csg shoe	Present csg				
MD.Float colar	Present csg				
MD.Top of csg/liner	Present csg/liner				
MD.Well	Well TD				

TVD.Well	True Vertical Depth for deviated wells				
MD.Plug	Plugged TD (if well is plugged back)				
Length.csg.overlap (L_1)	Planned Length into previous csg				
Length.openhole (L_2)	Length of Open hole interval				
Length.rat.hole (L_R)	Length of Rat hole				
Length.shoe.track (h_c)	Distance from thrust collar to csg shoe				
MD.TOC	Theoretical				
MD.TOC	From CBL or similar tool (Actual)				
Theoretical TOC	Planned Height of cement in annulus referred from MD.Well				
Observed TOC	Actual Height of cement derived from CBL or similar tool				
V.Cement (V1)	The pumped volume				
2. *Calculated/Estimated Results*					
V.Cement.Theoretical (V2)	Includes; Annular spaces in L1 & L2, hole sump and shoe trac				
Theoretical displ. ratio (V1/V2)	Ratio of pumped cement volume to theoretical volume				
Actual displacement efficiency	The ratio of observed TOC to theoretical TOC				
V.CBL (V3)	V.Cement derived from CBL or similar tools				
V4	V.Cement that has lost to the formation during pumping				
V3/V1	Fraction of the pumped volume that has actually filled the annulus				

Unless otherwise stated, all cases used bit diameter of the current section as the wellbore mean diameter, D_m for the open hole interval; this is because determination of exact D_m involves another tedious mathematical (numerical) work as seen in equations (3) and (4). Theoretical volume to be displaced was in all cases estimated (calculated) by using equation (10). Different conversion factors used in each calculation are presented in Appendix D.

According to Amanullah & Banik (1987), the length of cement column from thrust collar to the casing shoe h_c is usually 15 – 20 m depending on diameter of the casing in use. In estimating $V_{theoretical}$, small liners used the value of h_c = 15 m and was increased linearly to 20 m as casing diameter increased. However, when the float collar and casing shoe depths are both specified, the exact value was used instead.

In cases where pumped cement volume was given as sacks of dry cement, the provided slurry yield (cubic feet/sack) was used to obtain pumped volume of slurry in cubic feet. That is, volume of slurry equals to slurry yield multiplied by number of sacks. See appendix D, conversion factors.

Fraction of pumped volume (V3/V1) is the ratio of cement volume (V3) derived from CBL logs or similar tools to the pumped volume (V1). It is an indication of how big the volume of cement had lost to the formation relative to the pumped volume (V1).

Cement quality in this work was assessed based on three parameters estimated from the raw data:

- Theoretical displacement ratio. This is the ratio of the pumped cement volume to theoretical volume. For good quality cement job, the ratio has to be above one, preferably 1.4 or more to account for excess volume due to hole over gauge in open hole intervals
- Actual displacement efficiency. This is the ratio of observed TOC to theoretical TOC. The observed TOC is usually seen through CBL or similar tools. A quality job is expected to give this quantity equal to one
- The ratio of observed volume based on CBL or similar tools to pumped volume. This is the fraction of the pumped volume that has actually filled the annulus. For no loss displacement this has a value equal to one

5.3. Group A: Normal Cases from the Field and Published Literature

These are the cases where most of the cementing problems discussed under chapters 2.2, 2.3 and 4.2 are eliminated. They have the following assumed characteristics:

- Theoretical displacement ratio above one, and preferably 1.4 to account for excess volume due to hole over gauge in open hole intervals.
- Observed TOC may be lower than the planned TOC but this should not be a problem. For example if there is enough casing overlap filled with cement or present casing is hanged at sea bed, low observed TOC is not a problem.
- The ratio of observed volume based on CBL or similar tools to pumped volume should be approaching one
- Actual displacement efficiency close to one
- The overall displacement process should not lead to compromised cement

To elaborate the characteristics of good cement jobs, analyses of four cases with successful annular filling together with cases from literature are presented so as to learn the difference between normal jobs (successful annular filling) and failed jobs (unsuccessful annular filling).

Ontology engineering and Causal relations were not presented for good cement jobs. Here focus was to check displacement efficiency. Case template presented in Table 5 was used for this purpose. Some more cases were presented without their analysis on excel, only failure evaluation through CBR and stating the mentioned characteristics of normal jobs.

Good Case I:

Well Name and Section: 34/10-C-47, section 8 ½”
Data Source: Statoil A.S.

From EoW report for well 34/10-C-47, an example of good cement job of the 7” Liner in well section 8 ½” is presented. Well schematic is shown in Figure 21. Analysis and details of the case are found in Appendix A; “Analyses of Good Cases”, Table 9.

Cement loss was anticipated in this zone since it crossed several faults as seen in Table 6. It was decided to pump 40 m^3 cement in advance (squeeze in faults to avoid losses) followed by 20 m^3 spacer and finally 30 m^3 foamed cement.

Table 6: Faults interpreted from well data and seismic data which are crossed by 8 ½” well section in *Good case I* (Christophersen, Gjerde, & Valdem, 2007)

Faults/Formation	Measured Depth [m RKB]	True Vertical Depth [m MSL]	Section
Fault S3 (S5/S3)	3210	1975	8 ½”
Fault S3	3425	1999	
Fault S3	3555	1998	
Fault S2 (S5/S3)	3810	2000	
Fault S2	4080	2005	
Fault S2	4150	1999	
Fault S3	4350	1985	

As seen in Table 9, the three parameters; theoretical displacement ratio (1.216), actual displacement efficiency (0.988) and fraction of the pumped volume that has actually filled annulus (0.808), all indicate a good cement job. The slight failure in sealing the leak in 9 5/8” casing was cured by squeezing cement into the top of the 7” liner lap.

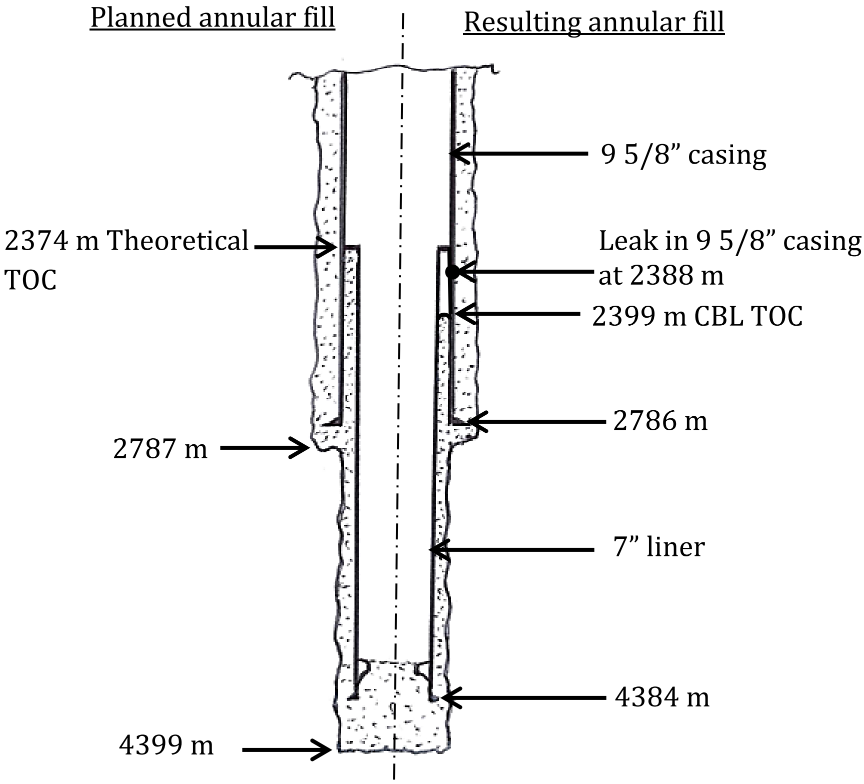

***Figure 21**: Well schematic; Planned and attained TOC’s for well 34/10-C-47 in Good case I. The unsealed hole in 9 5/8” casing was sealed successfully by squeezing cement into the 7” liner top anomalies*

Good Case II:

Well Name and Section: 2/2-5, section 12 ¼” (9 5/8" csg)
Data Source: AGR Database (Saga Petroleum A.S.)

From EoW report for well 2/2-5, an example of good cement job of the 9 5/8" casing in well section 12 ¼” is presented. Well schematic is shown in Figure 22. Analysis and details of the case are found in Appendix A; “Analyses of Good Cases”, Table 10.

As seen in Table 10, the three parameters; theoretical displacement ratio (1.513), actual displacement efficiency (0.961) and fraction of the pumped volume that has actually filled annulus (0.631), except the last, others indicate a good cement job.

A slight fall in observed TOC was detected by CBL logs (planned and observed TOC’s were 2070 mMD and 2120 mMD respectively). Since the 9 5/8” casing was hanged at seabed, it is not possible for leak to occur and it was therefore decided not to squeeze the lap and drilling continued to the next section.

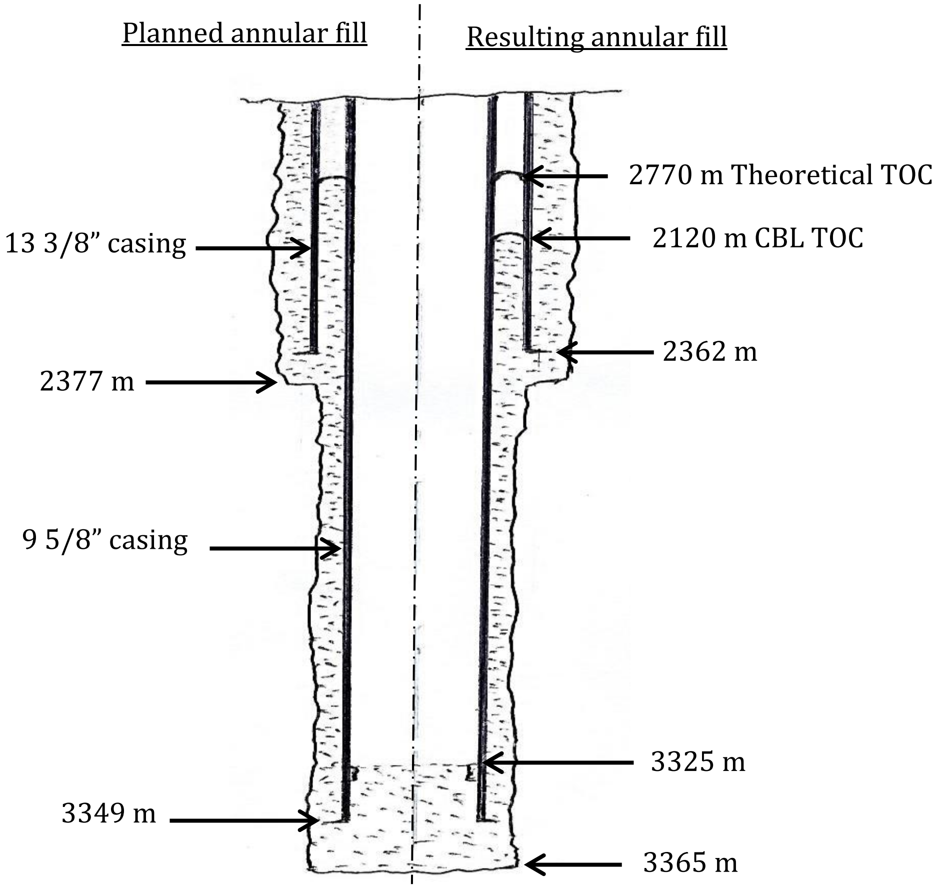

Figure 22: Well schematic; Planned and attained TOC's for well 2/2-5 in Good case II. The observed TOC has enough overlap to protect the 9 5/8" casing from corrosion

Good Case III:

Well Name and Section: 3/4-1, section 17 ½" (13 3/8" casing)
Data Source: AGR Database (Amoco Norway Oil Company)

From EoW report for well 3/4-1, an example of good cement job for the 13 3/8" casing in well section 17 ½" is presented. Well schematic is shown in Figure 23. Analysis and details of the case are found in Appendix A; "Analyses of Good Cases", Table 11.

As seen in Table 11, the three parameters; theoretical displacement ratio (1.533), actual displacement efficiency (0.965) and fraction of the pumped volume that has actually filled annulus (0.582), except the last parameter others indicate a good cement job.

Although continuous returns were observed throughout the job, material balance of the pit volumes before and after the job indicated a loss of 100 bbl (15.9 m^3) of drilling fluid. This loss did not affect the cement displacement to a great extent since there was enough pumped volume.

A slight fall in observed TOC was detected by CBL logs (planned and observed TOC's were 183 mMD and 230 mMD respectively). This fall in observed TOC proved not to halt the sealing since there was still enough length of cement overlap (see Figure 23) and drilling continued to the next section.

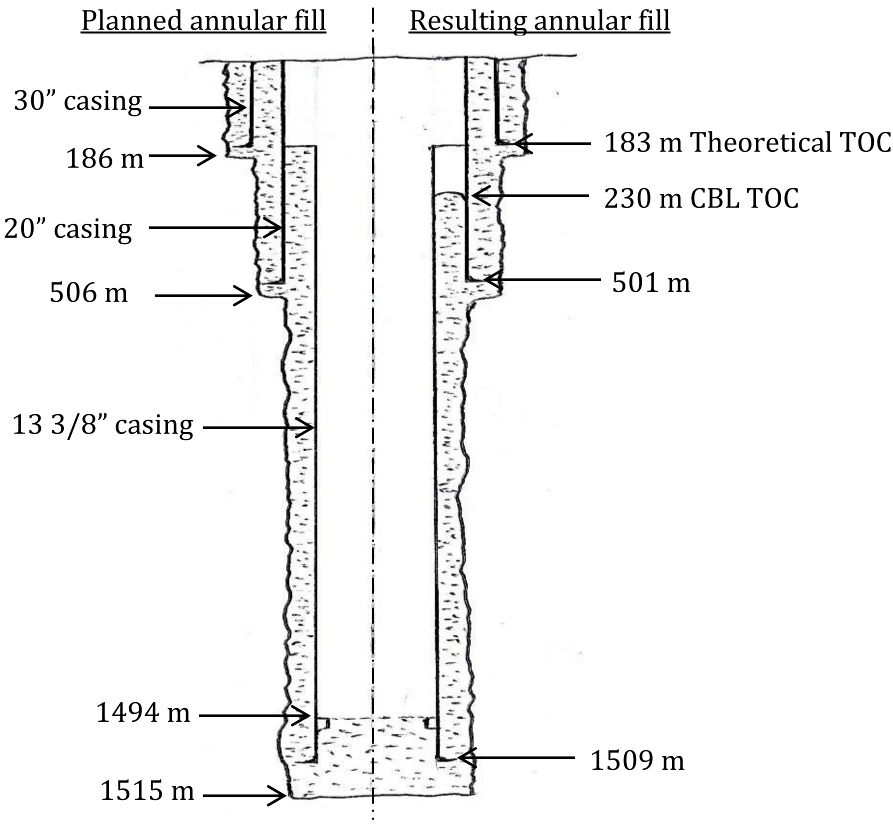

Figure 23: *Well schematic; Planned and attained TOC's for well 3/4-1 in Good case III. The observed TOC had enough overlap to protect the 13 3/8" casing from corrosion, or if necessary can easily be squeezed from the 13 3/8" casing top*

Good Case IV:

Well Sections/Liners: 8 ½" and 6" / 7" and 5 ½"
Data Source: Published literature

A case study from published literature, Hayden et al., (2011) is described here under to show the contrast between good and bad cement bond, and ambiguity of the indicated TOC.

The purpose of cementing in this case study was to isolate the depleted (XX3 Sand) and non-depleted/additional (XX4 Sand) reservoir zones. Interpretation of cement integrity was challenging due to lack of good contrast of the cement bond for the cemented and non-cemented pipe. The resulting top of competent cement seen by normal CBL attenuation logs happened to be in four different levels. This led to uncertainty of whether there was a good or bad cement job in this interval, see Figure 24.

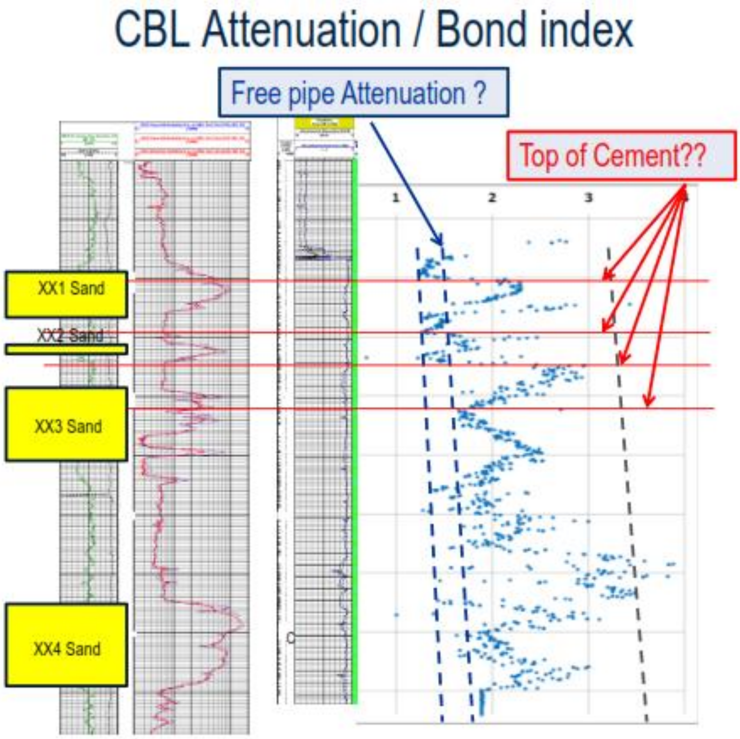

Figure 24: *Normal CBL attenuation logs indicating four TOC's due to lack of contrast between cemented and non-cemented pipes. Additional log data are needed to clearly show the specific TOC (Hayden et al., 2011)*

An improved cement integrity evaluation technique helped to clear the doubt by specifying one correct TOC as seen in Figure 25. The technique included Variable Density Logs and Flexural Attenuation map. These concluded that the resulting TOC was enough to offer good zonal isolation (above the XX3 sand) and hence a good cement job for this section was attained.

A good cement job is seen below the indicated TOC whereas above it and all the way to the planned TOC there is a poor cement bond (job). But this was not a problem since the zones were sufficiently isolated by the already attained TOC.

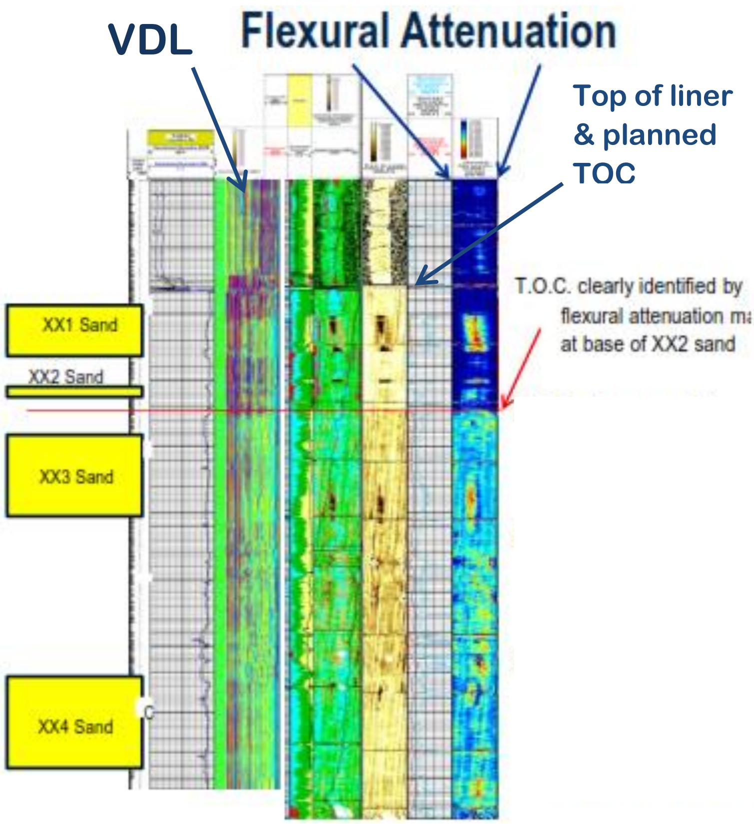

***Figure 25:** Clear TOC indicated by VDL and Flexural Attenuation map. A good contrast between cemented- and free pipe intervals is now clearly seen (Hayden et al., 2011)*

Good Case V:

Well Name and Section: 34/10-37A, Section 12 ¼" (Casing 9 5/8")
Data Source: AGR Database (Statoil A.S.)

From EoW report for well 34/10-37A, an example of good cement job for the 9 5/8" casing in well section 12 ¼" is presented. Well schematic is shown in Figure 26. Analysis and details of the case are found in Appendix A; "Analyses of Good Cases", Table 12.

Cementing was done by pumping 28.6 m^3 slurry in two stages; 10.7 m^3 lead cement and 17.975.06 m^3 tail cement. Theoretical volume to be displaced was found to be 27.944 m^3. Under normal circumstances this could be defined as a poor cement job because of low displacement ratio.

As seen in Table 12, with exception of theoretical displacement ratio (1.023), actual displacement efficiency (0.951) and fraction of the pumped volume that has actually filled annulus (0.929), indicate a good cement job.

The theoretical displacement ratio indicates a bad cement job in this case, but since there was low cement loss and continuous returns were observed throughout the job, and likewise no part of casing was left free then the overall cement job is perceived to be good and successful.

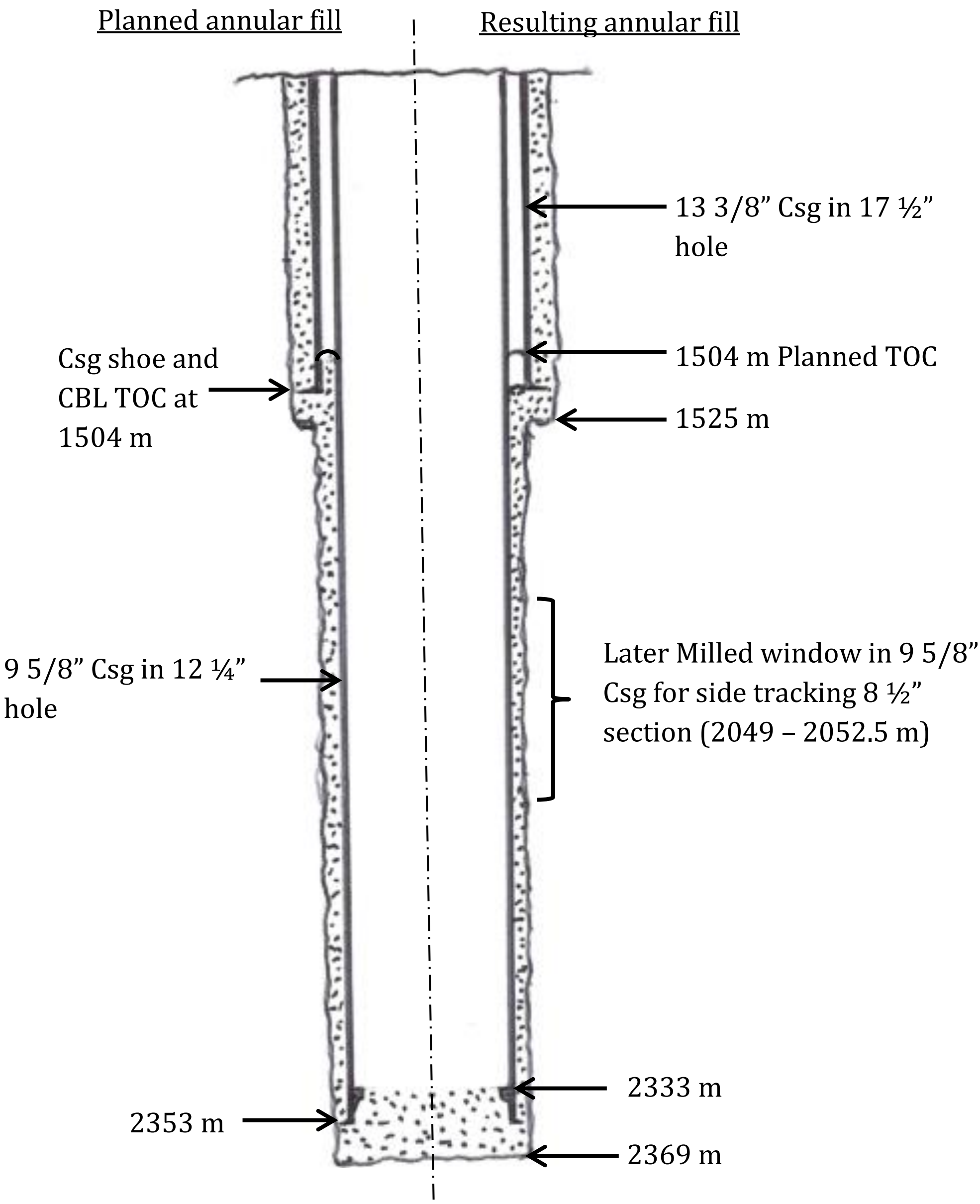

Figure 26: *Well schematic; Planned and resulting cement job for well 34/10-37A in Good case V. The pumped cement was low but since there were no huge cement losses to formation, the overall job was good.*

5.4. Group B: Failed Cases from the Field

The cases with unsuccessful filling of the annulus are the ones exhibiting poor cement displacement jobs. To prove the phenomenon of poor cement jobs, cement quality of these cases is checked. Theoretical displacement ratio, actual displacement efficiency and fraction of pumped volume that has actually filled the annulus are the three parameters used to check the quality of cement job in these cases. For this matter the data related to displacement efficiency presented in Table 5 was also used in failed cases to determine the three parameters for checking cement quality.

Further, in failed cases interest was also to determine the potential problem causes. This was achieved through ontology engineering. Table 7 (Failure ontology Template) presents data related to ontology engineering and Table 8 (Causal relations Template) presents the data used for working the causal relations of the resulting errors and failures derived from logic outputs of ontology engineering. Table 8 also gives an explanation of possible chances of occurrence of the errors in each case.

In Table 7 all or most of the symptoms, both detectable in real-time (s) and those known before execution of cementing operation (ss) are presented together with their description. A logic operator/output is given to help the process of selecting effective symptoms which are then used to determine the possible chances for occurrences of the errors and failures (causal relations) for a particular failure case.

Suggestions of how the situation could have been avoided and sketch of well schematic to supplement other visual information of the problem area were given at the end of analysis of each failure case.

Table 7: Failure Ontology Template presenting data related to ontology engineering of the failed cases

Available Observations "Symptoms (s)/(ss)"	Description/Options	Basic Operator or Source	Logic Output
Build/Drop Section Inside Csg (ss)	When (MD.Csg.Shoe) - MD.Build/drop upper > 0		
Build/Drop Section Inside Openhole (ss)	When (MD.Csg.Shoe - MD).Build/drop lower < 0; When inside openhole leads to csg decentralization		
Cement V/Theoretical V Low (ss)	When Vc/Vc.th < 1.5 - 1.25 - 1.0		
Csg Ann Slot Narrow (ss)	When (Bit.Size - OD.Csg) < 4 - 3 - 2 in Previous bit!!		
Fm Above Charged (ss)	Increasing reservoir pressure due to natural frature in the formation or drilling fluid entering the reservoir through later induced fractures		
Fm Fault Expected (ss)	Fault intersect may add to the complexity of cementing the well		
Fm Special Expected (ss)	Here it will be defined in particular case		
Losses Expected (ss)	Known before drilling		
Well Depth High (ss)	Well TVD > 2 - 3 - 4 km		
Well Depth Shallow (ss)	When Well.TVD < 2 – 1.5 - 1 km		
Well Inclination High (ss)	When Well Incl. > 60 degrees. See WellPlan /EoW		
Well Inclination Low (ss)	When Well Inclination < 30 degrees		
Well Inclination Medium (ss)	When Well Inclination between 30 and 60 degrees		
Well Length High (ss)	Measured Well Length > 3 - 4 - 5 kmMD		
Well Openhole Long (ss)	If (MD.Well-MD.Prev.Csg.Shoe) > 0.4 - 0.75 - 1 kmMD		
Csg Ann P High (s)	Can lead to induced LC		
Displacement Pressure High (s)	When; Frac D - ECD < 1.0 - 0.5 - 0 kg/l		
Displacement Rate High (s)	When leads to pressure build up in the annulus		
Losses Seepage (s)	Loss < 5 - 3.5 - 2 % of pump rate		
Losses Serious (s)	Loss > 5 - 10 - 15 % of pump rate		
Packoff (s)	Restriction to cement flow caused by accumulated cuttings		
Pressure Bleeding High (s)	Pressure drop rate > 5 - 10 - 15 psi/min		

Table 8: Causal relations Template

Available Observations "Symptoms (s)/(ss)"	Path strength	Explanation Strength	Target Error	Probability	Resulting Failures
Build/Drop Section Inside Csg (ss)					
Build/Drop Section Inside Openhole (ss)					
Cement V/Theoretical V Low (ss)					
Csg Ann Slot Narrow (ss)					
Fm Above Charged (ss)					
Fm Fault Expected (ss)					
Fm Special Expected (ss)					
Losses Expected (ss)					
Well Depth High (ss)					
Well Depth Shallow (ss)					
Well Inclination High (ss)					
Well Inclination Low (ss)					
Well Inclination Medium (ss)					
Decentralized csg/liner (ss)					
Well Length High (ss)					
Well Openhole Long (ss)					
Csg Ann P High (s)					
Displacement Pressure High (s)					
Displacement Rate High (s)					
Losses Seepage (s)					
Losses Serious (s)					
Packoff (s)					
Pressure Bleeding High (s)					
Total					

Failed Case 01:

Case Name:	Lost cement due to hole pack-off
Well Name and Section:	2/1-3, Section 8 ½”
Data Source:	AGR Database (*BP Petroleum development Ltd., Norway U.A.*)

From EoW report for well 2/1-3, a case of hole Pack-off leading to lost cement is noticed in well section 8 ½” during cementing operation of the 7” Liner. Well schematic is shown in Figure 27. Analysis and details of the case are found in Appendix B; “Analyses of Failed Cases”, Table 13, Table 14 and Table 15.

Cementing was done in two attempts. Slurry mixing problems was the reason for second attempt. Due to the mixing problem, the slurry used in the first attempt was reversed out and dumped. 208 barrels (33.068 m^3) of slurry was then pumped during the second attempt to cement a theoretical volume of 19.436 m^3. While pumping cement, the hole packed-off and most of the cement was lost to the formation. This caused pressure build up to 750 psi (51.7 bar) in the well leading to taking in an 11 bbl (1.75 m^3) kick which was then bled off to zero. After trip in, the mud was then conditioned to 1.71 SG and well was effectively killed.

After cleanup of the casing, CBL was run and showed the zone of lost circulation to be below 9 5/8” casing shoe. Poor or no cementation of the 7” liner lap was also detected. From the CBL, TOC was found to be at 3793 m which means the cement had failed to completely seal even the liner-open hole interval. That is no isolation of zones and which may eventually lead also to corrosion of the liner. Squeezing was unsuccessful because of hole pack-off. The huge loss of cement (18.389 m^3) led to unsuccessful filling of the annulus (low TOC) as planned and hence poor cement job in this section.

As seen in Table 13, with exception of theoretical displacement ratio (1.701), actual displacement efficiency (0.558) and fraction of the pumped volume that has actually filled annulus (0.444), both indicate a poor cement job. The pumped volume was enough but losses are the cause of poor cement job.

The issue could have been avoided by:

- Ensuring good hole cleaning prior to cement displacement
- Pumping a certain volume of cement in advance that comprises sufficient lost circulation additives to seal the leaking formation
- Pumping rate and pressure could have been reduced and hence avoid pressure build up in the annulus.

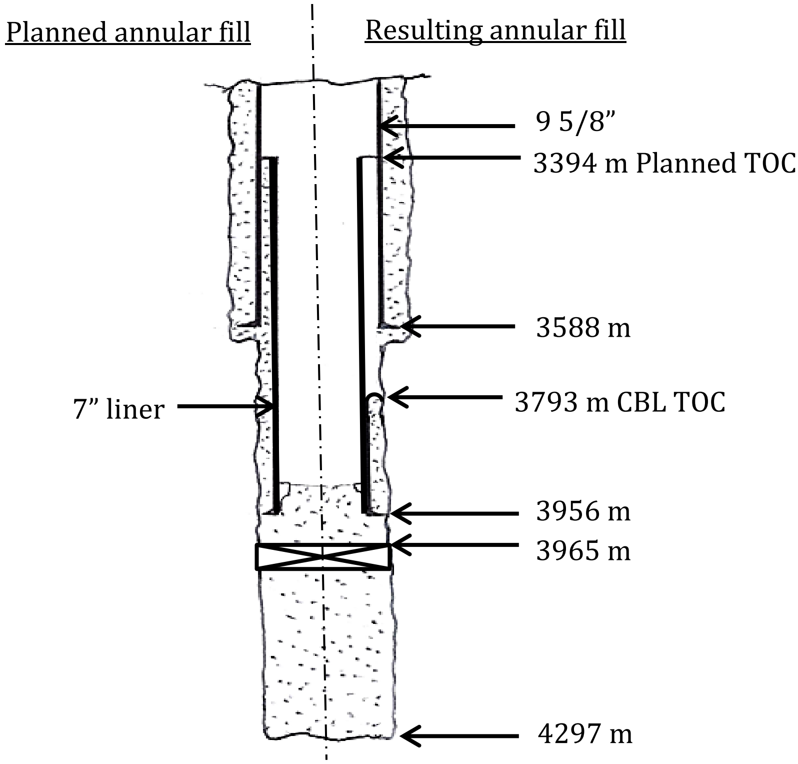

Figure 27: Well schematic; Planned and attained TOC's for well 2/1-3 in failed case 01. Squeezing was unsuccessful because of pack-off problems in the hole

Failed Case 02:

Case Name:	Lost cement and poor quality cement sheath in washouts
Well Name and Section:	2/1-4, Section 8 ½"
Data Source:	AGR Database (*BP Petroleum development Ltd., Norway U.A.*)

From EoW report for well 2/1-4, a case of lost cement and poor quality of cement sheath is noticed in well section 8 ½" during cementing operation of the 7" Liner. Well schematic is shown in Figure 28. Analysis and details of the case are found in Appendix B; “Analyses of Failed Cases”, Table 16, Table 17 and Table 18.

Cementing was done in two attempts. The first cementing attempt was unsuccessful because of failed air supply at the cementing equipment and the cement for this attempt was circulated out and dumped. A total of 12 hours 15 minutes were lost during the first attempt.

A second attempt was initiated. A total of 1241 cubic feet (35.141 m^3) cement was pumped in the second attempt to cement a theoretical volume of (19.876 m^3). The second attempt faced severe displacement problems because of the following problems:

1) This section was badly washed out in the interval 3823-3984 m (maximum of 15” by 23” elliptical). The wash outs led to poor hole cleaning and bad quality of the cement sheath
2) Special formation (loose sand) was penetrated in the washed out interval. Which led to poor bonding of cement and formation
3) Displacement pressure was very high (max. 1200 psi). It was twice as the pressure used in well 2/1-3 in the same area. This led to development of induced fractures and hence loosing cement.
4) Displacement rate was also high (7.5 bbl/min) for this narrow annulus. This led to annular pressure build up.

It is stated in EoW report for well 2/1-4 that CBL logs showed good cement bond from 7” liner shoe to 4000 mMD, except from some poor interval 4100 – 4130 mMD. Bad cements were seen from 4000 mMD to liner overlap at 3590 mMD which might be because of washouts.

From the observed TOC of 4000 mMD, it is clear that out of the 35.141 m^3 pumped cement only 14.754 m^3 was used to fill the annulus leaving the 20.387 m^3 being lost to the formation.

As seen in Table 16, with exception of theoretical displacement ratio (1.768), actual displacement efficiency (0.562) and fraction of the pumped volume that has actually filled annulus (0.42), both indicate a poor cement job.

The situations could have been avoided by:

- Conditioning mud prior to cement displacement to ease hole cleaning especially in the washouts
- Volume of pumped cement could be increased to squeeze part of it to the formation and stop further loss
- Cement displacement pressure could be lowered to reduce the cement loss to the formation

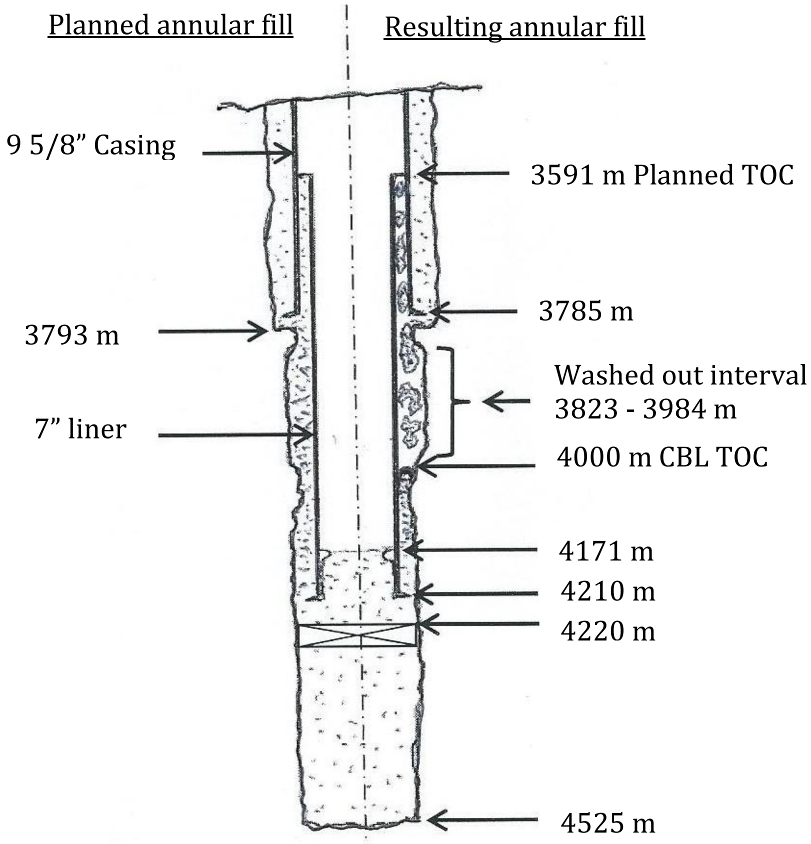

Figure 28: *Well schematic; Planned and attained TOC's for well 2/1-4 in Failed Case 02. Bad cement is seen from 4000 m to 3591 m due washouts. Squeezing was unsuccessful because of compromised cement in this interval*

Failed Case 03:

Case Name:	Risk of casing corrosion due to insufficient pumped cement volume and loss of cement to formation
Well Name and Section:	2/2-2, Section 17 ½”
Data Source:	AGR Database (Saga Petroleum A.S.)

From EoW report for well 2/2-2, a case of low TOC (casing exposed to formation) is noticed in well section 17 ½” during cementing operation of the 13 3/8” casing. Well schematic is shown in Figure 29. Analysis and details of the case are found in Appendix B; “Analyses of Failed Cases”, Table 19, Table 20 and Table 21.

Cementing was done by pumping cement volume of 4124 cu.ft, (87.226 m^3) in two stages. 3549 cu.ft (75.06 m^3) lead cement and 575 cu.ft (12.16 m^3) tail cement. Theoretical volume to be displaced was found to be 84.872 m^3. This led to poor displacement ratio.

It is stated in the EoW report that CBL log was run and indicated the TOC to be at 1220 mMD while the planned TOC was anticipated to 706 mMD. The low observed TOC left the casing free (not cemented) and exposed to formation, leading to a high risk of casing corrosion which can develop a hole on it.

Poor cement job in this section was due to:

1) Insufficient pumped cement volume. Pumped 87.226 m^3 cement to fill 84.872 m^3 annular space
2) High displacement pressure (2500psi or 172 bar) which led to losses of both cement and mud during displacement

As seen in Table 19, the three parameters; theoretical displacement ratio (1.028), actual displacement efficiency (0.592) and fraction of the pumped volume that has actually filled annulus (0.593), all indicate a poor cement job.

The situation could have been avoided by:

- Increasing the volume of pumped cement
- Reducing displacement rates
- Reducing displacement pressure

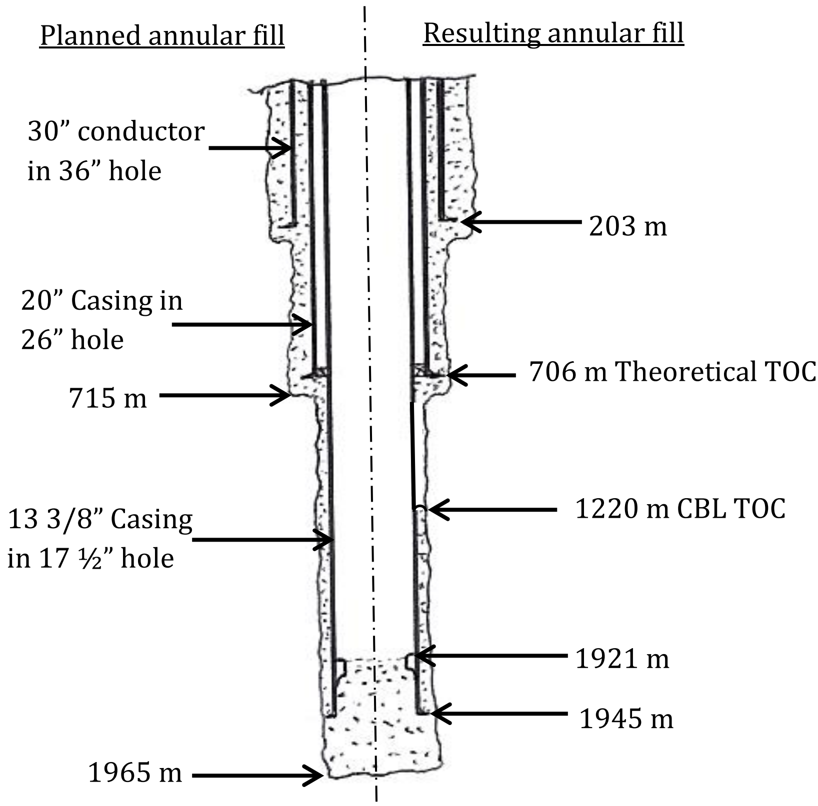

Figure 29: *Well schematic; Planned and attained TOC’s for well 2/2-2 in Failed Case 03. It was not possible to Squeeze from seabed and therefore the 13 3/8” casing is exposed to corrosion.*

Failed Case 04:

Case Name:	Poor cement bond and Poor cement coverage in inclined well section
Well Name and Section:	7/12-3A, Section 8 ½”
Data Source:	AGR Database (*BP Petroleum development of Norway A/S*)

From EoW report for well 7/12-3A, a case of poor cement- bond and sheath (annular coverage) is noticed in inclined well section 8 ½” during cementing operation of the 7” Liner. Well schematic is shown in Figure 30. Analysis and details of the case are found in Appendix B; “Analyses of Failed Cases”, Table 22, Table 23 and Table 24.

Cementing was done in a single stage by pumping 504 cu.ft (14.272 m^3) cement slurry to fill a theoretical volume of 11.083 m^3.

EoW report states that CBL/VDL logs were run and indicated inadequate cement coverage in the lower side of dropping-off section. This led to poor cement bond with the formation and liner. The poor bonding on the drop-off section happened from 3710mMD (Observed TOC) to the liner lap. Squeezing was only successful on the liner lap and some perforated parts of the drop-off section.

Poor cement job in this section was caused by:

1) Well inclination of 29º which led to casing decentralization in this section (narrow annulus in a low side of drop-off section)
2) Drop-off section inside the open hole
3) High displacement pressure which led to build up of high pressure in the annulus and eventually loss of slurry to formation

EoW report also states, the same problem happened on the top side of buildup of 12 ¼” section of the same well as seen in Figure 30.

As seen in Table 22, the three parameters; theoretical displacement ratio (1.288), actual displacement efficiency (0.671) and fraction of pumped volume that has actually filled annulus (0.501), all indicate a poor cement job.

The situation could have been avoided by:

- Increasing number of casing centralizers to withstand bending resistance (forces) of the casing string
- Reducing displacement pressure
- Good well design to reduce or avoid high inclinations

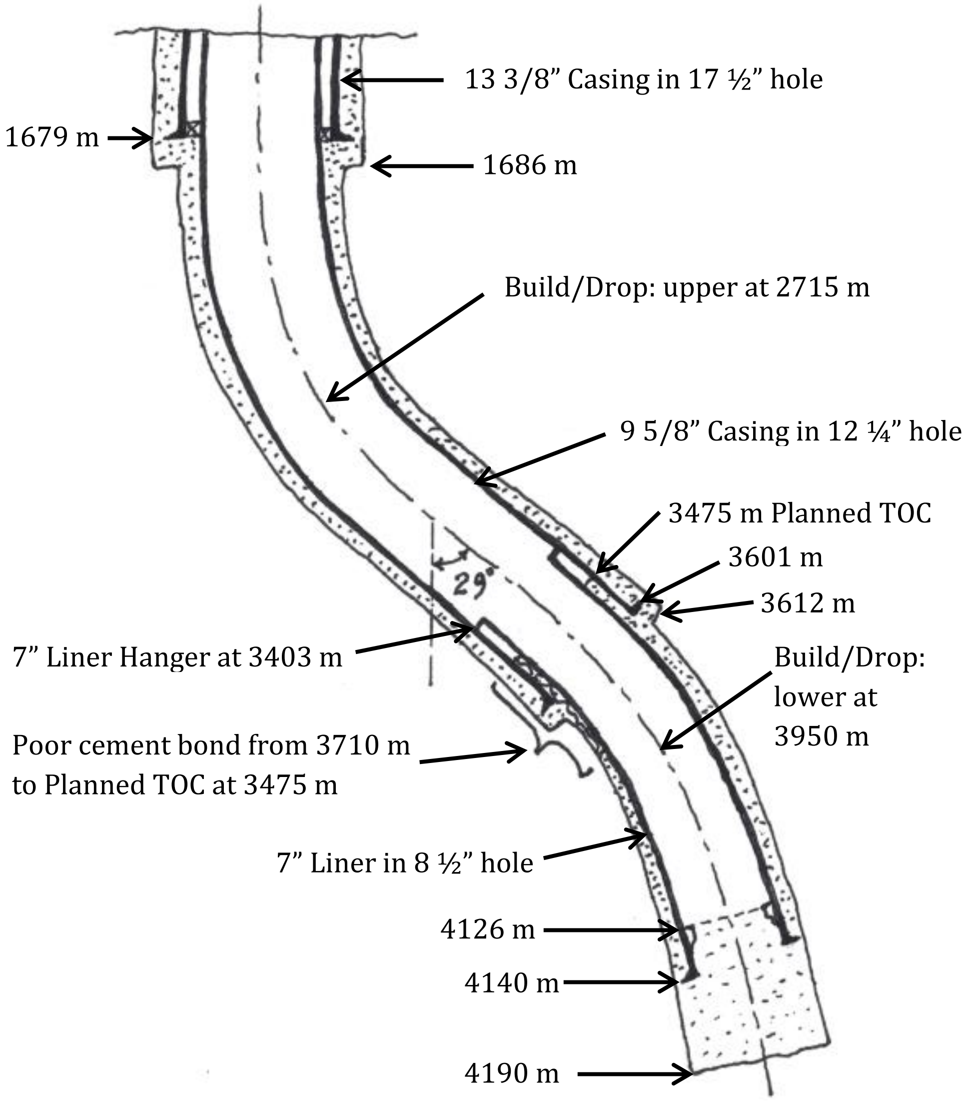

Figure 30: *Well schematic; showing resulting cement job (Poor cement bond and coverage) in narrow annulus of section 8 ½”for an inclined well 7/12-3A of Failed Case 04.*

6. Self-assessment

6.1. Applicability of this work

The analyzed cases of failed cement jobs provide evidences of failure of cement slurry in filling the annulus during oil well cementing. Since the analysis involves assessment of several symptoms of failure (ontology engineering and causal relations), it is possible to forecast similar cement job failures and their corresponding root causes in future well cementing operations using this knowledge.

6.2. Shortcomings of this work

Presentation of results for the analyzed cases of failed cement jobs in this work has some limitations that make the failures (evidences) difficulty to be understood with ease. The limitations are:

- Lack of CBL logs for the cemented wells to support the analyses of cement jobs and confirm (verify) the stated problem. The data sources used in this work only came with digital data, well schematics and explanations of cement jobs. No CBL logs were attached to the EoW reports, although they were run.
- Well schematic presented for each failed cement job is a pictorial representation of nature and location of the problem based on problem visualization of the author of this work. The data sources contained well schematics for only the planned cement jobs.
- The raw data needed for analysis of both good and bad cases were many and some of them were not given in EoW reports (Data sources). The missing ones were then intelligently guessed to

complete the evaluation and this might in some ways impair the reality.

- This work presented four different types of evidences of poor cement jobs related to displacement of cements which are:
  - ✓ Lost cement due to hole pack-off
  - ✓ Lost cement and poor quality of cement sheath caused by washouts
  - ✓ Low TOC leading to risk of casing corrosion caused by insufficient pumped slurry volume and loss of cement to formation
  - ✓ Poor cement bond and Poor cement coverage in inclined well section caused by casing decentralization

  In fact, there are other types of poor cement jobs which needed to be considered. These include:
  - ✓ Compromised cements
  - ✓ Inefficient of the cementing additives
  - ✓ Erroneous thickening time

6.3. Future Improvements

In order for the analyses of job failures to be more evident, the following are the suggestions for future improvements of the work:

- Presentation of results from the analyzed cases of failed cement jobs should include also the extracts or snapshots of CBL logs for the target area or well section. This will make the problem justifiable and easily understood by observing the targeted area.
- Consulting owners of different data sources so as to have a variety of information and verifications for a particular failure case.

- The analyses should include as many problem types of failures as possible so as to document the findings and use the knowledge as a helpful tool in forecasting similar failures in the future.
- In some cases CBL or sonic logs of the cemented well might not be enough to verify the problem, for this case, more advanced cement evaluation techniques (if available) might be needed to justify the problem. An example of this scenario is found in Good Case IV.
- Experiments should be done to see and verify how cements displaced with different flow regimes, viscosities and densities settle and behave in the annulus after completing the cement job. This is important to improve the understanding of cement tops as they are used to assess quality of cement jobs.

7. Conclusion

Based on the work of finding evidences of poor cement displacement jobs the following conclusions were drawn:

- Knowledge of well cementing operations was enhanced through the analysis of both good and poor cement jobs in this work
- The knowledge and understanding obtained from the findings and analysis of failed cases can be used to forecast type of poor cement jobs relating to displacement in future well cementing operations and hence reduce cement job failures
- All wells (successful and failed jobs) had lower TOC's than theoretical (planned TOC's). In fact, the observed TOC's were typically 60% and 96% in average of the theoretical heights for failed and successful jobs respectively.
- 75% (3 out of 4) of the failed jobs happened in 8 ½" section while 60% (3 out of 5) of successful jobs were in 12 ¼" or bigger sections. This means that the more narrower the annulus becomes the more challenging the cement job becomes
- The causes of failures in each case were as follows:
    - ✓ Failed Case 01 was due to hole pack-off
    - ✓ Failed Case 02 was due to washouts in weak formation
    - ✓ Failed Case 03 was due to insufficient pumped cement volume
    - ✓ Failed Case 04 was due to drop-down section of casing in the open hole interval which led to casing eccentricity.

- Actual and planned displacement efficiencies as tools for assessing quality and success level of cement jobs were in all the cases checked by focusing on the four basic items which are:
    - ✓ The annular volume to be cemented
    - ✓ The volume of cement that was injected to fill the annulus
    - ✓ Theoretical or planned height of cement in the annulus and
    - ✓ The resulted height of cement in the annulus from CBL or similar tools

8. Nomenclature

8.1. Abbreviations

Ann	Annulus/Annular
API	American Petroleum Institute
bbl	Barrels
BP	British Petroleum
CBL	Cement Bond Log
CBR	Case Based Reasoning
CET	Ultrasonic Cement Mapping Tool
CME	Chemical and Mining Engineering
CMT	Cement Mapping Logs
Csg	Casing
cu.ft	Cubic Feet
deg	Degrees
e.g.	for example
ECD	Equivalent Circulating Density
EoW	End of Well
ERD	Extended Reach Drilling
etc	etcetera (and so on)
Fm	Formation
Frac D	Fracture Density
ft	Foot
GoM	Gulf of Mexico
GOR	Gas-Oil Ratio
GUI	Graphical User Interface
HTHP	High Temperature-High Pressure
IADC	International Association of Drilling Contractors
ID	Inner/Inside Diameter
in	inch
lb	Pound
LC	Lost Circulation
LCP	Liquid Cement Premix
lpm	Liters per minute
Ltd	Limited
LWD	Logging While Drilling
m	meter
max	Maximum
MD	Measured Depth
Mhz	Mega Hertz
min	Minute(s)
MSL	Mean Sea Level
NPT	Non-Productive Time
NTNU	Norges Teknisk-Naturvitenskapelige Universitet
N/A	Not Applicable
OD	Outside Diameter

OFU	Oil Field Unit
P	Pressure
PC	Personal Computers
Prev	Previous
psi	Pounds per square inch
RKB	Rotary Kelly Bushing
RTDD	Real-Time Drilling Data
s	Symptom(s)
SG	Specific Gravity
SI	Système International
SP	Spontaneous Potential
SPE	Society of Petroleum
ss	static symptom
TD	Total Depth
TOC	Top of Cement
TVD	True Vertical Depth
UDSM	University of Dar es Salaam
USI	Ultrasonic Imaging Logs
VDL	Variable Density Displays
w/no	with no
WBM	Water Based Mud

8.2. Symbols

ε	Displacement Efficiency (Ratio)
"	inch
º	Degrees
ΔT	Transit time [micro-seconds per foot]
D	Outside diameter of the casing string [m]
d	Inside diameter of the casing string [m]
d_{av}	Average hole diameter [m
d_j	Diameter of the corresponding *n*th section [m]
D_m	Wellbore mean diameter according to cavernogram of the section [m]
dp/dx	Pressure gradient [Pa/m]
d_{pipe}	Pipe diameter
$f(h)$	Function of height
h	Height
h_c	Distance from the thrust collar to the casing shoe, usually 15 – 20 m cement column
$k > 1$	Marginal capacity factor, usually 1.2 – 1.3 for safety reasons
L_1	Planned distance into previous casing (casing overlap length) [m]
L_2	Length of open hole from first casing shoe to the next casing shoe [m]
L_c	Length of the cementing interval [m]
L_j	Length of the *n*th section [m]
L_R	Length of rat hole (hole sump) [m]
N_{Re}	Reynolds number

r	Stream radius [m]
R	Pipe radius [m]
V	Volume
v	Stream velocity [m/s]
V_{cs}	Cement Slurry Volume
v_m	Mean fluid velocity [m/s]
v_{max}	Maximum fluid velocity in the center [m/s]
μ	Dynamic Fluid viscosity, [Pas]
ρ	Density of flowing fluid [kg/m^3]

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10. Appendices

Appendix A: Analyses of ***Good Cases*** done in excel

Table 9: Data related to Displacement efficiency for ***Good Case I***

Well Name and Section: 34/10-C-47, Section 8 1/2"					
Data Source: Statoil					
Data related to Displacement Efficiency					
1. Raw data					
Available drilling/Cementing Parameter	**Description/Options**	**OFU**		**SI**	**Probability**
		Quantity	Unit	Quantity	
Bit size	Previous section	12.25	in	0.311	100
Bit size	Present section	8.5	in	0.216	100
ID.Csg	Previous csg (P-110, 53.5 lb/ft) Table 25	8.535	in	0.217	100
ID.Csg	Present csg (L-80, 29 lb/ft) Table 25	6.184	in	0.157	100
OD.Csg	Present csg	7	in	0.178	100
MD.Csg shoe	Previous csg			2786.000	100
MD.Csg shoe	Present csg			4384.000	100
MD.Float colar	Present csg			4367.000	90
MD.Top of csg/liner	Present csg/liner			2374.000	100
MD.Build/Drop.Upper	Its approximate mid-point. Upper is normally inside csg			2370.000	90
MD.Build/Drop. Lowest	Its approximate mid-point. Could well be in the openhole. If only one build/drop then upper is also the lowest!			2370.000	90
Fm Special Expected	2 options: Yes or No --> Yes; (to be stated what special)	No			
Fm Fault Expected	2 options: Yes or No --> Yes; could lead cement loss	Yes			
Losses Expected	2 options: Yes or No --> Yes; in Tare	Yes			
MD.Well	Well TD			4399.000	100
TVD.Well	True Vertical Depth for deviated wells			1982.000	100
Length.csg.overlap (L1)	Planned Length into previous csg			412.000	100
Length.openhole (L2)	Distance from current csg shoe to previous csg shoe			1598.000	100
Length.rat.hole (LR)	Length of Rat hole (Hole sump)			15.000	100
Length.shoe.track (hc)	Distance from thrust collar to csg shoe			17.000	100
Well inclination	Average angle of the last hundreds metres	90	^{0}		95
Cement Loss	Loss rate to the formation (% of pump rate)	7	%		75
Frac D - ECD	Narrow pressure margin during cement displacement	1.15	Kg/l		80
Well Packed-off	2 Options: Yes or No --> Yes; leads to cement loss	No			
Pressure Bleeding High	Pressure drop rate during pressure testing is high	8.7	psi/min		100
MD.TOC	Theoretical			2374.000	90
MD.TOC	From CBL log run (Actual MD of competent cement)			2399.000	100
Theoretical TOC	Planned Height of cement in annulus refferred from MD.Well			2025.000	90
Observed TOC	Actual Height of cement derived from CBL			2000.000	100
V.Cement (V1)	The pumped volume			30.000	100
2. Calculated/Estimated Results					
V.Cement.Theoretical (V2)	Includes; Annular spaces in L1 & L2, hole sump and shoe track			24.670	
Theoretical displ. ratio (V1/V2)	Ratio of pumped cement volume to Theoretical volume			1.216	
Actual displ. efficiency	The ratio of Observed TOC to Theoretical TOC			0.988	
V.CBL (V3)	V.Cement Derived from CBL			24.251	
V4	V.Cement that has lost to the formation during pumping (known after CBL run)			5.749	
V3/V1	Fraction of the pumped volume that has actually filled the annulus			0.808	

Table 10: Data related to Displacement efficiency for ***Good Case II***

Well Name and Section: 2/2-5, section 12 1/4" (9 5/8" csg)					
Data Source: AGR Database (Saga Petroleum A.S.)					
Data related to Displacement Efficiency					
1. Raw data					
Available drilling/Cementing Parameter	**Description/Options**	**OFU**		**SI**	**Probability**
		Quantity	Unit	Quantity	
Bit size	Previous section	17.5	in	0.445	100
Bit size	Present section	12.25	in	0.311	100
ID.Csg	Previous csg (P-110, 72 lb/ft) Table 25	12.347	in	0.314	100
ID.Csg	Present csg (P-110, 53.5 lb/ft) Table 25	8.535	in	0.217	100
OD.Csg	Present csg	9.625	in	0.244	100
MD.Csg shoe	Previous csg			2362.000	100
MD.Csg shoe	Present csg			3349.000	100
MD.Float colar	Present csg			3325.000	90
MD.Top of csg/liner	Present csg/liner			89.000	100
MD.Build/Drop.Upper	Its approximate mid-point. Upper is normally inside csg				
MD.Build/Drop. Lowest	Its approximate mid-point. Could well be in the openhole. If only one build/drop then upper is also the lowest!				
Fm Special Expected	2 options: Yes or No --> Yes; (to be stated what special)	No			
Fm Fault Expected	2 options: Yes or No --> Yes; could lead cement loss	No			
Losses Expected	2 options: Yes or No --> Yes; in Tare	No			
MD.Well	Well/Section TD			3365.000	100
TVD.Well	True Vertical Depth for deviated wells			3364.960	100
Length.csg/cement.overlap (L1)	Planned Length of cement into previous csg			292.000	100
Length.openhole (L2)	Distance from current csg shoe to previous csg shoe			987.000	100
Length.rat.hole (LR)	Length of Rat hole (Hole sump)			16.000	100
Length.shoe.track (hc)	Distance from thrust collar to csg shoe			24.000	100
Well inclination	Average angle of the last hundreds metres	1.9	^{0}		95
Cement Loss	Loss rate to the formation (% of pump rate)	3	%		85
Frac D - ECD	Narrow pressure margin during cement displacement	1.17	Kg/l		80
Well Packed-off	2 Options: Yes or No --> Yes; leads to cement loss	No			
Pressure Bleeding High	Pressure drop rate during pressure testing is high	2.3	psi/min		90
MD.TOC	Theoretical			2070.000	90
MD.TOC	From CBL log run (Actual MD of competent cement)			2120.000	90
Theoretical TOC	Planned Height of cement in annulus refferred from MD.Well			1295.000	90
Observed TOC	Actual Height of cement derived from CBL			1245.000	100
V.Cement (V1)	The pumped volume (Lead 44 + Tail 16)			60.000	100
2. Calculated/Estimated Results					
V.Cement.Theoretical (V2)	Includes; Annular spaces in L1 & L2, hole sump and shoe track			39.649	
Theoretical displ. ratio (V1/V2)	Ratio of pumped cement volume to Theoretical volume			1.513	
Actual displ. efficiency	The ratio of Observed TOC to Theoretical TOC			0.961	
V.CBL (V3)	V.Cement Derived from CBL			37.842	
V4	V.Cement that has lost to the formation during pumping (known after CBL run)			22.158	
V3/V1	Fraction of the pumped volume that has actually filled the annulus			0.631	

Table 11: Data related to Displacement efficiency for ***Good Case III***

Well Name and Section: 3/4-1, section 17 1/2" (13 3/8" csg)					
Data Source: AGR Database (Amoco Norway Oil Company)					
Data related to Displacement Efficiency					
1. Raw data					
Available drilling/Cementing Parameter	**Description/Options**	**OFU**		**SI**	**Probability**
		Quantity	Unit	Quantity	
Bit size	Previous section	26	in	0.660	100
Bit size	Present section	17.5	in	0.445	100
ID.Csg	Previous csg (X-56, 133 lb/ft) Table 25	18.73	in	0.476	100
ID.Csg	Present csg (N-80, 72 lb/ft) Table 25	12.347	in	0.314	100
OD.Csg	Present csg	13.375	in	0.340	100
MD.Csg shoe	Previous csg			501.000	100
MD.Csg shoe	Present csg			1509.000	100
MD.Float colar	Present csg			1494.000	90
MD.Top of csg/liner	Present csg/liner			183.000	100
Fm Special Expected	2 options: Yes or No --> Yes; (to be stated what special)	No			
Fm Fault Expected	2 options: Yes or No --> Yes; could lead cement loss	No			
Losses Expected	2 options: Yes or No --> Yes; in Tare	No			
MD.Well	Well/Section TD			1515.000	100
TVD.Well	True Vertical Depth for deviated wells			1514.950	100
Length.csg/cement.overlap (L1)	Planned Length of cement into previous csg			318.000	100
Length.openhole (L2)	Distance from current csg shoe to previous csg shoe			1008.000	100
Length.rat.hole (LR)	Length of Rat hole (Hole sump)			6.000	100
Length.shoe.track (hc)	Distance from thrust collar to csg shoe			15.000	100
Well inclination	Average angle of the last hundreds metres	0.9	^{0}		95
Cement Loss	Loss rate to the formation (% of pump rate)	4	%		85
Frac D - ECD	Narrow pressure margin during cement displacement	1.11	Kg/l		80
Well Packed-off	2 Options: Yes or No --> Yes; leads to cement loss	No			
Pressure Bleeding High	Pressure drop rate during pressure testing is high	2.7	psi/min		90
MD.TOC	Theoretical			183.000	90
MD.TOC	From CBL log run (Actual MD of competent cement)			230.000	90
Theoretical TOC	Planned Height of cement in annulus refferred from MD.Well			1332.000	90
Observed TOC	Actual Height of cement derived from CBL			1285.000	100
V.Cement (V1)	The pumped volume (Lead 685 bbl + Tail 229 bbl)	914	bbl	145.310	100
2. Calculated/Estimated Results					
V.Cement.Theoretical (V2)	Includes; Annular spaces in L1 & L2, hole sump and shoe track			94.794	
Theoretical displ. ratio (V1/V2)	Ratio of pumped cement volume to Theoretical volume			1.533	
Actual displ. efficiency	The ratio of Observed TOC to Theoretical TOC			0.965	
V.CBL (V3)	V.Cement Derived from CBL			84.586	
V4	V.Cement that has lost to the formation during pumping (known after CBL run)			60.724	
V3/V1	Fraction of the pumped volume that has actually filled the annulus			0.582	

Table 12: Data related to Displacement efficiency for ***Good Case V***

Well Name and Section: 34/10-37A, Section 9 5/8"					
Data Source: AGR Database (Statoil A.S.)					
Data related to Displacement Efficiency					
1. Raw data					
Available drilling/Cementing Parameter	**Description/Options**	**OFU**		**SI**	**Probability**
		Quantity	Unit	Quantity	
Bit size	Previous section	17.5	in	0.445	100
Bit size	Present section	12.25	in	0.311	100
ID.Csg	Previous csg (P-110, 72 lb/ft) Table 25	12.347	in	0.314	100
ID.Csg	Present csg (P-110, 53.5 lb/ft) Table 25	8.535	in	0.217	100
OD.Csg	Present csg	9.625	in	0.244	100
MD.Csg shoe	Previous csg			1504.000	100
MD.Csg shoe	Present csg			2353.000	100
MD.Float colar	Present csg			2338.000	80
MD.Top of csg/liner	Present csg/liner			163.000	100
Fm Fault Expected	2 options: Yes or No --> Yes; could lead cement loss	No			
Losses Expected	2 options: Yes or No --> Yes; in Tare	Yes			
Fm Special Expected	2 options: Yes or No --> Yes; leads to disintegrated fm	No			
MD.Well	Well/Section TD			2369.000	100
TVD.Well	True Vertical Depth for deviated wells			2369.000	100
Length.csg.overlap (L1)	Planned Length into previous csg			49.000	100
Length.openhole (L2)	Distance from current csg shoe to previous csg shoe			849.000	100
Length.rat.hole (LR)	Length of Rat hole (Hole sump)			16.000	100
Length.shoe.track (hc)	Distance from thrust collar to csg shoe			15.000	80
Well inclination	Average angle of the last hundreds metres	1.5	0		100
Cement Loss	Loss rate to the formation (% of pump rate)	2	%		90
Well Packed-off	2 Options: Yes or No --> Yes; leads to cement loss	No			
MD.TOC	Theoretical			1455.000	90
MD.TOC	From CBL log run (Actual MD of competent cement)			1500.000	90
Theoretical TOC	Planned Height of cement in annulus refferred from MD.Well			914.000	100
Observed TOC	Actual Height of cement derived from CBL			869.000	100
V.Cement (V1)	The pumped volume (lead = 10.7 and Tail = 17.9)			28.600	100
2. Calculated/Estimated Results					
V.Cement.Theoretical (V2)	Includes; Annular spaces in L1 & L2, hole sump and shoe track			27.944	
Theoretical displ. ratio (V1/V2)	Ratio of pumped cement volume to Theoretical volume			1.023	
Actual displ. efficiency	The ratio of Observed TOC to Theoretical TOC			0.951	
V.CBL (V3)	V.Cement Derived from CBL			26.576	
V4	V.Cement that has lost to the formation during pumping (known after CBL run)			2.024	
V3/V1	Fraction of the pumped volume that has actually filled the annulus			0.929	

Appendix B: Analyses of ***Failed Cases*** done in excel

Table 13: Data related to Displacement efficiency for ***Failed Case 01***

Case Name: Lost cement due to hole packoff in well 2/1-3, section 8 1/2"					
Data Source: AGR Database (BP Petroleum development Ltd., Norway U.A.)					
Data related to Displacement Efficiency					
1. Raw data					
Available drilling/Cementing Parameter	**Description/Options**	**OFU**		**SI**	**Probability**
		Quantity	Unit	Quantity	
Bit size	Previous section	12.25	in	0.311	100
Bit size	Present section	8.5	in	0.216	100
ID.Csg	Previous csg (N-80 47 lb/ft) Table 25	8.535	in	0.217	100
ID.Csg	Present csg (XTL-N-80 32 lb/ft) Table 25	6.094	in	0.155	100
OD.Csg	Present csg	7	in	0.178	100
MD.Csg shoe	Previous csg			3588.000	100
MD.Csg shoe	Present csg			3956.000	100
MD.Top of csg/liner	Present csg/liner			3394.000	100
Fm Fault Expected	2 options: Yes or No --> Yes; could lead cement loss	No			
Losses Expected	2 options: Yes or No --> Yes; in Tare	Yes			
MD.Well	Well TD			4297.000	100
TVD.Well	True Vertical Depth for deviated wells			4295.500	97
MD.Plug	Plugged TD (if well is plugged back)			3965.000	100
Length.csg.overlap (L1)	Planned Length into previous csg			194.000	100
Length.openhole (L2)	Distance from current csg shoe to previous csg shoe			368.000	100
Length.rat.hole (LR)	Length of Rat hole (Hole sump)			341.000	100
Length.shoe.track (hc)	Distance from thrust collar to csg shoe			15.000	80
Well inclination	Average angle of the last hundreds metres	0	0		90
Cement Loss	Loss rate to the formation (% of pump rate)	17	%		70
Frac D - ECD	Narrow pressure margin during cement displacement	0.63	Kg/l		70
Well Packed-off	2 Options: Yes or No --> Yes; leads to cement loss	Yes			
Pressure Bleeding High	Pressure drop rate during pressure testing is high	9.6	psi/min		70
MD.TOC	Theoretical			3394.000	90
MD.TOC	From CBL log run (Actual)			3793.000	100
Theoretical TOC	Planned Height of cement in annulus referred from Well TD			903.000	95
Observed TOC	Actual Height of cement derived from CBL			504.000	95
V.Cement (V1)	The pumped volume	208	bbl	33.068	100
2. Calculated/Estimated Results					
V.Cement.Theoretical (V2)	Includes; Annular spaces in L1 & L2, hole sump and shoe track			19.436	
Theoretical displ. ratio (V1/V2)	Ratio of pumped cement volume to Theoretical volume			1.701	
Actual displ. efficiency	The ratio of Observed TOC to Theoretical TOC			0.558	
V.CBL (V3)	V.Cement Derived from CBL			14.679	
V4	V.Cement that has lost to the formation during pumping (known after CBL run)			18.389	
V3/V1	Fraction of the pumped volume that has actually filled the annulus			0.444	

Table 14: Data related to Ontology engineering for ***Failed Case 01***

Available Observations "Symptoms (s)/(ss)"	Description/Options	Basic Operator or Source	Logic Output
Cement V/Theoretical V Low (ss)	When Vc/Vc.th < 1.5 - 1.25 - 1.0	G36/G38	0
Csg Ann Slot Narrow (ss)	When (Bit.Size - OD.Csg) < 4 - 3 - 2 in (current section)	E11-E14	3
Fm Above Charged (ss)	Increasing reservoir pressure due to natural frature in the formation or drilling fluid entering the reservoir through later induced fractures	No	0
Fm Fault Expected (ss)	Fault intersect may add to the complexity of cementing the well	E18	0
Losses Expected (ss)	Known before drilling	E19	1
Well Depth High (ss)	Well TVD > 2 - 3 - 4 km	G21	3
Well Depth Shallow (ss)	When Well.TVD < 2 – 1.5 - 1 km	G21	0
Well Inclination High (ss)	When Well Incl. > 60 degrees. See WellPlan /EoW	E27	0
Well Inclination Low (ss)	When Well Inclination is between 5 and 30 degrees	E27	0
Well Inclination Medium (ss)	When Well Inclination between 30 and 60 degrees	E27	0
Vertical Well (ss)	When Well Inclination between 0 and 5 degrees	E27	1
Well Length High (ss)	Measured Well Length > 3 - 4 - 5 kmMD	G20	2
Well Openhole Long, "L2+LR" (ss)	If (MD.Well-MD. Prev.Csg.Shoe) > 0.4 - 0.75 - 1 kmMD	G24+G25	1
Csg Ann Pressure High (s)	Can lead to induced LC	Yes	1
Displacement Pressure High (s)	When; Frac D - ECD < 1.0 - 0.5 - 0 kg/l	E29	1
Displacement Rate High (s)	When leads to pressure build up in the annulus	Yes	1
Losses Seepage (s)	Loss < 5 - 3.5 - 2 % of pump rate (+)	E28	0
Losses Serious (s)	Loss > 5 - 10 - 15 % of pump rate (+)	E28	3
Packoff (s)	Restriction to cement flow caused by accumulated cuttings	E30	1
Pressure Bleeding High (s)	Pressure drop rate > 5 - 10 - 15 psi/min	E31	1

Table 15: Causal Relations for ***Failed Case 01***

Symptoms/ Observations	Path strength	Explanation Strength	Target Error	Probability	Resulting Failures
Packoff	1	2.4	Cement Not Sufficiently displaced	0.27	Lost cement, Kick and overall cement job failure
Casing ann. P High	0.8				
Csg ann slot narrow	0.4				
Well length high	0.2				
Packoff	1	2.2	Cement Sheath Quality low	0.25	
Losses serious	0.8				
Csg ann slot narrow	0.4				
Losses serious	1	4.2	Leak Behind Casing	0.48	
Packoff	0.6				
Pressure bleeding high	0.8				
Displacement Pressure High	0.8				
Displacement Rate High	0.8				
Well Openhole long	0.2				
Total		**8.8**		**1.00**	

Table 16: Data related to Displacement efficiency for ***Failed Case 02***

Case Name: Lost cement and poor quality cement sheath in washouts of well 2/1-4, sec 8 1/2"

Data Source: AGR Database (BP Petroleum development Ltd., Norway U.A.)

Data related to Displacement Efficiency

1. Raw data

Available drilling/Cementing Parameter	Description/Options	OFU		SI	Probability
		Quantity	Unit	Quantity	
Bit size	Previous section	12.25	in	0.311	100
Bit size	Present section	8.5	in	0.216	100
ID.Csg	Previous csg (N-80, 47 lb/ft) Table 25	8.681	in	0.220	100
ID.Csg	Present csg (N-80, 29 lb/ft) Table 25	6.184	in	0.157	100
OD.Csg	Present csg	7	in	0.178	100
MD.Csg shoe	Previous csg			3785.000	100
MD.Csg shoe	Present csg			4210.000	100
MD.Float colar	Present csg			4171.000	100
MD.Top of csg/liner	Present csg/liner			3591.000	100
Fm Fault Expected	2 options: Yes or No --> Yes; could lead cement loss	No			
Losses Expected	2 options: Yes or No --> Yes; in Tare	Yes			
Fm Special Expected	2 options: Yes or No --> Yes; leads to disintegrated fm	Yes			
MD.Well	Well TD			4525.000	100
TVD.Well	True Vertical Depth for deviated wells			4524.000	95
MD.Plug	Plugged TD (if well is plugged back)			4220.000	100
Length.csg.overlap (L1)	Planned Length into previous csg			194.000	100
Length.openhole (L2)	Distance from current csg shoe to previous csg shoe			425.000	100
Length.rat.hole (LR)	Length of Rat hole (Hole sump)			315.000	100
Length.shoe.track (hc)	Distance from thrust collar to csg shoe			39.000	100
Well inclination	Average angle of the last hundreds metres	1.3	0		95
Cement Loss	Loss rate to the formation (% of pump rate)	19	%		75
Frac D - ECD low	Narrow pressure margin during cement displacement	0.4	Kg/l		80
Well Packed-off	2 Options: Yes or No --> Yes; leads to cement loss	No			
Pressure Bleeding High	Pressure drop rate during pressure testing is high	15	psi/min		100
MD.TOC	Theoretical			3591.000	90
MD.TOC	From CBL log run (Actual MD of competent cement)			4000.000	100
Theoretical TOC	Planned Height of cement in annulus refferred from MD.Well			934.000	100
Observed TOC	Actual Height of cement derived from CBL			525.000	100
V.Cement (V1)	The pumped volume (Lead 270 + Tail 971)	1241	cu.ft	35.141	100

2. Calculated/Estimated Results

V.Cement.Theoretical (V2)	Includes; Annular spaces in L1 & L2, hole sump and shoe track	19.876
Theoretical displ. ratio (V1/V2)	Ratio of pumped cement volume to Theoretical volume	1.768
Actual displ. efficiency	The ratio of Observed TOC to Theoretical TOC	0.562
V.CBL (V3)	V.Cement Derived from CBL	14.754
V4	V.Cement that has lost to the formation during pumping (known after CBL run)	20.387
V3/V1	Fraction of the pumped volume that has actually filled the annulus	0.420

Table 17: Data related to Ontology engineering for ***Failed Case 02***

Available Observations "Symptoms (s)/(ss)"	Description/Options	Basic Operator or Source	Logic Output
Cement V/Theoretical V Low (ss)	When Vc/Vc.th < 1.5 - 1.25 - 1.0	G38/G40	0
Csg Ann Slot Narrow (ss)	When (Bit.Size - OD.Csg) < 4 - 3 - 2 in (current section)	E11-E14	3
Fm Above Charged (ss)	Increasing reservoir pressure due to natural frature in the formation or drilling fluid entering the reservoir through later induced fractures	No	0
Fm Special Expected (ss)	Formation that leads to washouts (disintegrated wellbore)	E21	1
Fm Fault Expected (ss)	Fault intersect may add to the complexity of cementing the well	E19	0
Losses Expected (ss)	Known before drilling	E20	1
Well Depth High (ss)	Well TVD > 2 - 3 - 4 km	G23	3
Well Depth Shallow (ss)	When Well.TVD < 2 – 1.5 - 1 km	G23	0
Well Inclination High (ss)	When Well Incl. > 60 degrees. See WellPlan /EoW	E29	0
Well Inclination Medium (ss)	When Well Inclination between 30 and 60 degrees	E29	0
Well Inclination Low (ss)	When Well Inclination between 5 and 30 degrees	E29	0
Vertical Well (ss)	When Well Inclination between 0 and 5 degrees	E29	1
Well Length High (ss)	Measured Well Length > 3 - 4 - 5 kmMD	G22	2
Well Openhole Long, "L2+LR" (ss)	If (MD.Well-MD.Prev.Csg.Shoe) > 0.4 - 0.75 - 1 kmMD	G27+G26	1
Csg Ann Pressure High (s)	Can lead to induced LC	Yes	1
Displacement Pressure High (s)	When; Frac D - ECD < 1.0 - 0.5 - 0 kg/l	E31	2
Displacement Rate High (s)	leads to pressure build up in the annulus	Yes	1
Losses Seepage (s)	Loss < 5 - 3.5 - 2 % of pump rate (+)	E30	0
Losses Serious (s)	Loss > 5 - 10 - 15 % of pump rate (+)	E30	3
Packoff (s)	Restriction to cement flow caused by accumulated cuttings	E32	0
Pressure Bleeding High (s)	Pressure drop rate > 5 - 10 - 15 psi/min	E33	3

Table 18: Causal Relations for ***Failed Case 02***

Symptoms/ Observations	Path strength	Explanation Strength	Target Error	Probability	Resulting Failures
Fm special expected	1	1.6	Wellbore Enlarged	0.11	Lost cement and overall cement job failure (Poor quality of cement sheath)
Well open hole long	0.4				
Displacement Rate high	0.2				
Losses serious	1	2.8	Cement Not Sufficiently displaced	0.19	
Casing ann. P High	0.6				
Csg ann slot narrow	0.8				
Well depth high	0.2				
Well length high	0.2				
Fm special expected	0.6	3	Cement Sheath Quality low	0.20	
Well length high	0.4				
Losses expected	0.4				
Losses serious	0.8				
Csg ann slot narrow	0.8				
Pressure bleeding high	1	1.8	Leak in shoe	0.12	
Csg ann P. high	0.6				
Well open hole long	0.2				
Losses serious	1	5.8	Leak behind casing	0.39	
Well depth high	0.8				
Csg ann slot narrow	0.2				
Csg ann P. high	0.8				
Losses expected	0.6				
Pressure bleeding high	0.6				
Displacement Pressure High	0.8				
Displacement Rate High	0.8				
Well Openhole long	0.2				
Total		**15**		**1.00**	

Table 19: Data related to Displacement efficiency for ***Failed Case 03***

Case Name: Risk of csg corrosion due to insufficient pumped v.cement in well 2/2-2, sect. 17 1/2"					
Data Source: AGR Database (Saga Petroleum A.S.)					
Data related to Displacement Efficiency					
1. Raw data					
Available drilling/Cementing Parameter	**Description/Options**	**OFU**		**SI**	**Probability**
		Quantity	Unit	Quantity	
Bit size	Previous section	26	in	0.660	100
Bit size	Present section	17.5	in	0.445	100
ID.Csg	Previous csg (X-52, 133 lb/ft) Table 25	18.73	in	0.476	100
ID.Csg	Present csg (N-80, 72 lb/ft) Table 25	12.347	in	0.314	100
OD.Csg	Present csg	13.375	in	0.340	100
MD.Csg shoe	Previous csg			706.000	100
MD.Csg shoe	Present csg			1945.000	100
MD.Float colar	Present csg			1921.000	100
MD.Top of csg/liner	Present csg/liner			90.600	100
Fm Special Expected	2 options: Yes or No --> Yes; (to be stated what special)	No			
Fm Fault Expected	2 options: Yes or No --> Yes; could lead cement loss	No			
Losses Expected	2 options: Yes or No --> Yes; in Tare	Yes			
MD.Well	Section TD			1965.000	100
TVD.Well	True Vertical Depth for deviated well sections			1964.940	100
Length.csg/cement.overlap (L1)	Planned Length into previous csg (no cementation of lap)			0.000	100
Length.openhole (L2)	Distance from current csg shoe to previous csg shoe			1239.000	100
Length.rat.hole (LR)	Length of Rat hole (Hole sump)			20.000	100
Length.shoe.track (hc)	Distance from thrust collar to csg shoe			24.000	100
Well inclination	Average angle of the last hundreds metres	0.75	0		100
Cement Loss	Loss rate to the formation (% of pump rate)	12	%		75
Frac D - ECD	Narrow pressure margin during cement displacement	0.87	Kg/l		70
Well Packed-off	2 Options: Yes or No --> Yes; leads to cement loss	No			
MD.TOC	Theoretical			706.000	95
MD.TOC	From CBL log run (Actual)			1220.000	100
Theoretical TOC	Planned Height of cement in annulus referred from sect. TD			1259.000	95
Observed TOC	Actual Height of cement derived from CBL			745.000	95
V.Cement (V1)	The pumped volume (Lead 3549 cu.ft + Tail 575 cu.ft)	4124	cu.ft	87.226	100
2. Calculated/Estimated Results					
V.Cement.Theoretical (V2)	Includes; Annular spaces in L1 & L2, hole sump and shoe track			84.872	
Theoretical displ. ratio (V1/V2)	Ratio of pumped cement volume to Theoretical volume			1.028	
Actual displ. efficiency	The ratio of Observed TOC to Theoretical TOC			0.592	
V.CBL (V3)	V.Cement Derived from CBL			51.718	
V4	V.Cement that has lost to the formation during pumping			35.508	
V3/V1	Fraction of the pumped volume that has actually filled the annulus			0.593	

Table 20: Data related to Ontology engineering for ***Failed Case 03***

Available Observations "Symptoms (s)/(ss)"	Description/Options	Basic Operator or Source	Logic Output
Cement V/Theoretical V Low (ss)	When Vc/Vc.th < 1.5 - 1.25 - 1.0	G36/G38	2
Fm Fault Expected (ss)	Fault intersect may add to the complexity of cementing the well	E20	0
Fm Special Expected (ss)	Here it will be defined in particular case	E19	0
Losses Expected (ss)	Known before drilling	E21	1
Well Depth High (ss)	Well TVD > 2 - 3 - 4 km	G23	0
Well Depth Shallow (ss)	When Well.TVD < 2 – 1.5 - 1 km	G23	1
Well Inclination High (ss)	When Well Incl. > 60 degrees. See WellPlan /EoW	E28	0
Vertical Well (ss)	When Well Inclination between 0 and 5 degrees	E28	1
Well Inclination Low (ss)	When Well Inclination between 5 and 30 degrees	E28	0
Well Inclination Medium (ss)	When Well Inclination between 30 and 60 degrees	E28	0
Well Length High (ss)	Measured Well Length > 3 - 4 - 5 kmMD	G22	0
Well Openhole Long, "L2+LR" (ss)	If (MD.Well-MD.Prev.Csg.Shoe) > 0.4 - 0.75 - 1 kmMD	G25+G26	3
Csg Ann P High (s)	Can lead to induced LC	Yes	1
Displacement Pressure High (s)	When; Frac D - ECD < 1.0 - 0.5 - 0 kg/l	E30	1
Displacement Rate High (s)	When leads to pressure build up in the annulus	Yes	1
Losses Seepage (s)	Loss < 5 - 3.5 - 2 % of pump rate (+)	E29	0
Losses Serious (s)	Loss > 5 - 10 - 15 % of pump rate (+)	E29	2
Packoff (s)	Restriction to cement flow caused by accumulated cuttings	E31	0

Table 21: Causal Relations for ***Failed Case 03***

Symptoms/ Observations	Path strength	Explanation Strength	Target Error	Probability	Resulting Failures
Cement V/Theoretical V Low	1	3.8	Cement Not Sufficiently displaced	0.51	Lost cement and Insufficient annular fill leading to Risk of casing corrosion
Losses expected	0.8				
Casing ann. P High	0.4				
Losses serious	0.8				
Well Openhole long	0.6				
Well length high	0.2				
Losses serious	1	3.6	Leak Behind Casing	0.49	
Losses expected	0.8				
Displacement Pressure High	0.8				
Displacement Rate High	0.8				
Well Openhole long	0.2				
Total		**7.4**		**1.00**	

Table 22: Data related to Displacement efficiency for ***Failed Case 04***

Case Name: Poor cement- bond and coverage in inclined well 7/12-3A, Sec. 8 1/2"

Data Source: AGR Database (BP Petroleum Development of Norway A/S)

Data related to Displacement Efficiency

1. Raw data

Available drilling/Cementing Parameter	Description/Options	OFU		SI	Probability
		Quantity	Unit	Quantity	
Bit size	Previous section	12.25	in	0.311	100
Bit size	Present section	8.5	in	0.216	100
ID.Csg	Previous csg (N-80, 47 lb/ft) Table 25	8.681	in	0.220	100
ID.Csg	Present csg (N-80, 32 lb/ft) Table 25	6.094	in	0.155	100
OD.Csg	Present csg	7	in	0.178	100
MD.Csg shoe	Previous csg			3601.000	100
MD.Csg shoe	Present csg			4140.000	100
MD.Float colar	Present csg			4126.000	90
MD.Top of csg/liner	Present csg/liner			3403.000	100
MD.Build/Drop. Upper	Average depth of start and end of the deviation			2715.000	90
MD.Build/Drop. Lower	Average depth of start and end of the deviation			3950.000	90
Fm Fault Expected	2 options: Yes or No --> Yes; could lead cement loss	No			
Losses Expected	2 options: Yes or No --> Yes; in Tare	Yes			
Fm Special Expected	2 options: Yes or No --> Yes; leads to disintegrated fm	No			
MD.Well	Well TD			4190.000	100
TVD.Well	True Vertical Depth for deviated wells			4002.600	100
Length.csg.overlap (L1)	Planned Length into previous csg			198.000	100
Length.openhole (L2)	Distance from current csg shoe to previous csg shoe			539.000	100
Length.rat.hole (LR)	Length of Rat hole (Hole sump)			50.000	100
Length.shoe.track (hc)	Distance from thrust collar to csg shoe			14.000	100
Well inclination	Average angle of the last hundreds metres	29	0		100
Cement Loss	Loss rate to the formation (% of pump rate)	14	%		75
Frac D - ECD low	Narrow pressure margin during cement displacement	0.4	Kg/l		80
Well Packed-off	2 Options: Yes or No --> Yes; leads to cement loss	No			
Pressure Bleeding High	Pressure drop rate during pressure testing is high	11	psi/min		100
MD.TOC	Theoretical			3475.000	100
MD.TOC	From CBL log run (Actual MD of competent cement)			3710.000	80
Theoretical TOC	Planned Height of cement in annulus refferred from MD.Well			715.000	100
Observed TOC	Actual Height of cement derived from CBL			480.000	100
V.Cement (V1)	The pumped volume (Lead 270 + Tail 971)	504	cu.ft	14.272	100

2. Calculated/Estimated Results

V.Cement.Theoretical (V2)	Includes; Annular spaces in L1 & L2, hole sump and shoe track	11.083
Theoretical displ. ratio (V1/V2)	Ratio of pumped cement volume to Theoretical volume	1.288
Actual displ. efficiency	The ratio of Observed TOC to Theoretical TOC	0.671
V.CBL (V3)	V.Cement Derived from CBL	7.156
V4	V.Cement that has lost to the formation during pumping (known after CBL run)	7.116
V3/V1	Fraction of the pumped volume that has actually filled the annulus	0.501

Table 23: Data related to Ontology engineering for ***Failed Case 04***

Available Observations "Symptoms (s)/(ss)"	Description/Options	Basic Operator or Source	Logic Output
Cement V/Theoretical V Low (ss)	When Vc/Vc.th < 1.5 - 1.25 - 1.0	G39/G41	1
Csg Ann Slot Narrow (ss)	When (Bit.Size - OD.Csg) < 4 - 3 - 2 in (current section)	E11-E14	3
Build/Drop Section Inside Csg (ss) "No cement complication"	When (MD.Prev. Csg.Shoe) - MD.Build/drop upper> 0	G15-G19	1
Build/Drop Section Inside Openhole (ss) "Csg/liner decentralized"	When (MD.Prev. Csg.Shoe - MD.Build/drop lower < 0 ; When inside openhole leads to csg decentralization	G15-G20	1
Fm Above Charged (ss)	Increasing reservoir pressure due to natural frature in the formation or drilling fluid entering the reservoir through later induced fractures	No	0
Fm Special Expected (ss)	Formation that leads to washouts (disintegrated wellbore)	E23	0
Fm Fault Expected (ss)	Fault intersect may add to the complexity of cementing the well	E21	0
Losses Expected (ss)	Known before drilling	E22	1
Well Depth High (ss)	Well TVD > 2 - 3 - 4 km	G25	3
Well Depth Shallow (ss)	When Well.TVD < 2 – 1.5 - 1 km	G25	0
Well Inclination High (ss)	When Well Incl. > 60 degrees. See WellPlan /EoW	E30	0
Well Inclination Medium (ss)	When Well Inclination between 30 and 60 degrees	E30	0
Well Inclination Low (ss)	When Well Inclination between 5 and 30 degrees	E30	1
Vertical Well (ss)	When Well Inclination between 0 and 5 degrees	E30	0
Well Length High (ss)	Measured Well Length > 3 - 4 - 5 kmMD	G22	2
Well Openhole Long, "L2+LR" (ss)	If (MD.Well-MD.Prev.Csg.Shoe) > 0.4 - 0.75 - 1 kmMD	G27+G28	1
Csg Ann Pressure High (s)	Can lead to induced LC	Yes	1
Displacement Pressure High (s)	When; Frac D - ECD < 1.0 - 0.5 - 0 kg/l	E31	2
Displacement Rate High (s)	leads to pressure build up in the annulus	Yes	1
Losses Seepage (s)	Loss < 5 - 3.5 - 2 % of pump rate (+)	E31	0
Losses Serious (s)	Loss > 5 - 10 - 15 % of pump rate (+)	E31	2
Packoff (s)	Restriction to cement flow caused by accumulated cuttings	E33	0
Pressure Bleeding High (s)	Pressure drop rate > 5 - 10 - 15 psi/min	E34	2

Table 24: Causal Relations for ***Failed Case 04***

Symptoms/ Observations	Path strength	Explanation Strength	Target Error	Probability	Resulting Failures
Cement V/Theoretical V low	1	4.2	Cement Not Sufficiently displaced	0.28	Poor- cement bond and Poor cement coverage in inclined well section
Losses serious	0.6				
Casing ann. P High	0.6				
Csg ann slot narrow	0.6				
Losses expected	0.2				
Displacement Pressure High	0.4				
Well inclination	0.8				
Casing Decentralized	1	5.4	Cement Sheath Quality Low	0.36	
Cement V/Theoretical V low	0.8				
Well inclination	0.8				
Build/Drop section inside openhole	0.8				
Well openhole long (L2 + LR)	0.2				
Displacement Pressure High	0.8				
Csg ann slot narrow	1				
Well depth high	0.2	5.2	Leak behind casing	0.35	
Csg ann slot narrow	0.8				
Losses serious	0.8				
Csg ann P. high	1				
Losses expected	0.2				
Pressure bleeding high	0.6				
Displacement Pressure High	0.8				
Well Openhole long	0.8				
Total		**14.8**		**1.00**	

Appendix C: API Casing specifications (Dimensions & Bit Clearance Data) (J&S-Drilling, 2006).

Table 25: Extracts from API Casing specifications. Dimensions and Bit Clearance Data for 7” liner and 9 5/8” to 20” casings (J&S-Drilling, 2006).

O.D. (inch)	Nominal Weight T & C	Grade	Collapse Pressure (psi)	Internal Yield Pressure Minimum Yield (psi)				Joint Strength 1000 lbs			Body Yield 1000 lbs	Wall (inch)	I.D. (inch)	ift Diameter (inch)	
7.000	29.00	LS-65	6090	6630		6630	6630		492	628	549	0.408	6.184	6.059	
7.000	29.00	L-80	7020	8160		8160	8160		587	718	676	0.408	6.184	6.059	
7.000	29.00	HCL-80	9200	8160		8160	8160		655	780	676	0.408	6.184	6.059	
7.000	29.00	N-80	7020	8160		8160	8160		597	746	676	0.408	6.184	6.059	
7.000	29.00	HCN-80	9200	8160		8160	8160		655	780	676	0.408	6.184	6.059	
7.000	29.00	C-90	7580	9180		9180	9180		648	768	760	0.408	6.184	6.059	
7.000	29.00	HCP-110	9200	11220		11220	11220		797	955	929	0.408	6.184	6.059	
7.000	29.00	P-110	8530	11220		11220	11220		797	955	929	0.408	6.184	6.059	
7.000	32.00	HCL-80	10400	9060		9060	8460		738	832	745	0.453	6.094	5.969	6.000
7.000	32.00	N-80	8610	9060		9060	8460		672	823	745	0.453	6.094	5.969	6.000
7.000	32.00	HCN-80	10400	9060		9060	8460		738	860	745	0.453	6.094	5.969	6.000
9.625	47.00	HCL-80	7100	6870		6870	6870		1027	1234	1086	0.472	8.681	8.525	8.625
9.625	47.00	N-80	4760	6870		6870	6870		905	1161	1086	0.472	8.681	8.525	8.625
9.625	47.00	HCN-80	7100	6870		6870	6870		1027	1234	1086	0.472	8.681	8.525	8.625
9.625	47.00	C-90	5000	7720		7720	7720		987	1210	1221	0.472	8.681	8.525	
9.625	53.50	HCP-110	8850	10900		10900	10900		1422	1718	1710	0.545	8.535	8.379	8.500
9.625	53.50	P-110	7950	10900		10900	10900		1422	1718	1710	0.545	8.535	8.379	8.500
9.625	53.50	HCQ-125	8850	12390		12390	12390		1595	1890	1943	0.545	8.535	8.379	8.500
9.625	53.50	Q-125	8440	12390		12390	12390		1595	1890	1943	0.545	8.535	8.379	8.500
13.375	72.00	HCL-80	3470	5380	5380		5380	1181		1850	1661	0.514	12.347	12.191	###
13.375	72.00	N-80	2670	5380	5380		5380	1040		1693	1661	0.514	12.347	12.191	###
13.375	72.00	HCN-80	3470	5380	5380		5380	1192		1850	1661	0.514	12.347	12.191	###
13.375	72.00	HCP-110	3470	7400	7400		7400	1402		2221	2284	0.514	12.347	12.191	###
13.375	72.00	P-110	2890	7400	7400		7400	1402		2221	2284	0.514	12.347	12.191	###
13.375	72.00	HCQ-125	3470	8410	8410		8410	1577		2463	2596	0.514	12.347	12.191	###
20.000	106.50	N-80	770	3500	3500	3500	3500	1307	1514	2281	2450	0.500	19.000	18.812	
20.000	133.00	K-55	1500	3060	3060	3060	3060	1253	1453	2123	2125	0.635	18.730	18.542	
20.000	133.00	L-80	1600	4450	4450	4450	4450	1692	1958	2849	3091	0.635	18.730	18.542	
20.000	133.00	N-80	1600	4450	4450	4450	4450	1707	1976	2877	3091	0.635	18.730	18.542	
20.000	169.00	K-55	2500	3910	3230	3430	3380	1402	1732	2689	2692	0.812	18.376	18.188	

Appendix D: Conversion Factors

Inch to meter	0.0254
Barrels to cubic meters	0.1589825119
Cubic feet (cu.ft) to cubic meters	0.028316846
psi to bar	0.0689655