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I also thank the University of Stavanger for giving me the opportunity to complete my study, and I thank all the professors and students that I have worked with and gained all the progress thanks to them.

Abstract

This work brings up some important aspects of cementing procedure with the aim of reducing WOC time, avoiding remedial cementing and referring to some new technologies regarding plug and abandonment. In the beginning, a general overview of cement composition and behavior is given to give the reader an understanding of some important aspects of cement which will lead to better understanding of the challenges and solutions.

Different sources have been studied to give a general overview of cement and cementing procedures and to point out the correct steps and the potential failures in order to perform the cementing job in the best way possible and thus avoid any remedial job which is time-consuming, and time equals cost.

In addition, this thesis highlights some researches that confirm the possibility of reducing the wait on cement time which is followed by the oil companies nowadays, as well as referring to new technologies which saves time worth millions of dollars during well plug and abandonment.

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Abbreviations

USD	United States Dollar
GoM	Gulf of Mexico
OPC	Ordinary Portland Cement
CaCO3	Calcium Carbonate
RPM	Rotations Per Minute
ISO	International Organization for Standardization
API	American Petroleum Institute
MSR	Moderate Sulfate Resistance
HSR	High Sulfate Resistance
CaCl2	Calcium chloride
BWOC	By Weight Of Cement
Fe2O3	Hematite
FeTiO3	Ilmenite
BaSO4	Barite
PNS	Polynapthalenesulfonate
PVA	Poly Vinyl Alcohol
HEC	Hydroxyl Ethyl Cellulose
UCA	Ultrasonic Cement Analyzer
CHA	Cement Hydration Analyzer
WOC	Wait On Cement
POOH	pull out of the hole
PV	Plastic Viscosity
YP	Yield Point
ECD	Equivalent Circulating Density
OD	Outer Diameter
CO2	Carbone Dioxide
H2S	Hydrogen Sulfide
NOK	Norwegian Kroner
Bpm	Barrels per minute
Psi	pounds per square inch
Bc	Bearden consistency

1 OIL WELL CEMENTING

1.1 Introduction

Nobody can deny from the integrity of primary cementing job as good completion heavily relies on it. Failure to primary cementing job costs a lot to the oil and gas industry. About USD 450 million are spent in remedial cementing operations when 15% of the primary cementing operations get failed in serving its purpose [1]. In the US Gulf of Mexico (GoM), about 8000 to 11000 wells have an issue with sustained casing pressure (Figure 1) [2]. Insufficient pressure balancing is the main reason behind these failures. Due to this, any fluid can penetrate into the annulus filled with cement during the job. Therefore, the quality of the cementing job is very critical for long-termwell performance.

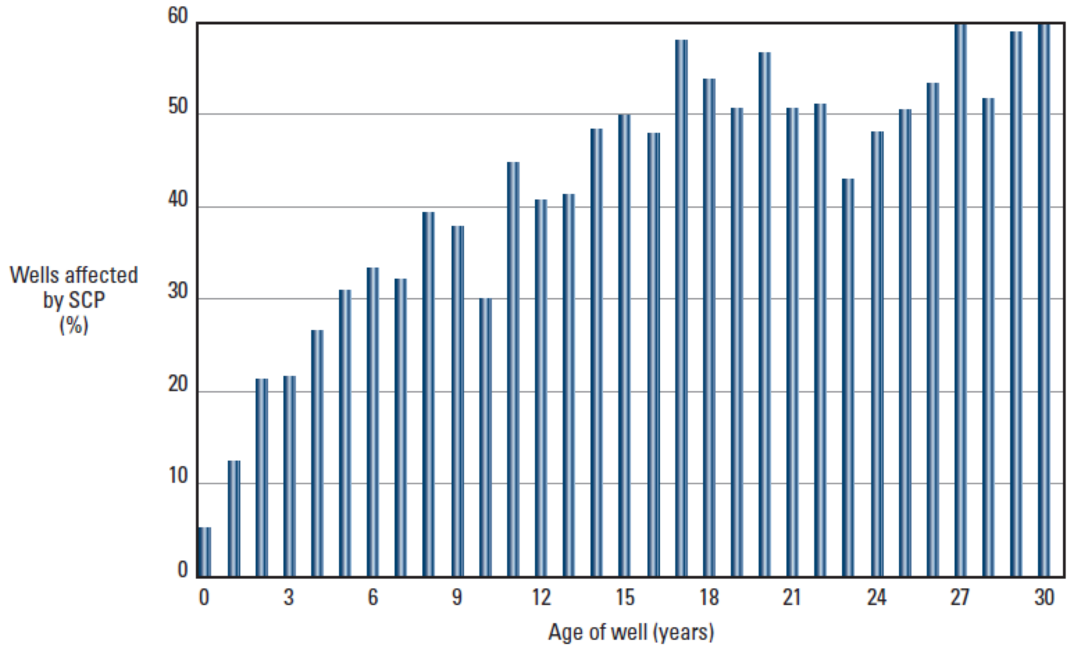

Figure 1 Comparison of age of wells with well affected by Sustained Casing Pressure [2]

Well productivity directly getsaffected by the quality of cement job during the whole life of the well whether it is in drilling, production, intervention or abandonment phase. Although oil well cement have low matrix permeability (in microdarcy ranges according to literature),the life of this low permeability can become very short due to the conditions that the well may be exposed to during different stages. Among these circumstances, cracking, debonding and shear failure are worth mentioning. Due to the production process, cracking can be induced to the cement as the temperature and pressure fluctuate, especially in gas wells. These variables cause the casing and cement to expand and contract which eventually create cracks in the cement sheath. Debonding can also occur between cement/pipe and cement/rock. Cement shrinkage, variations in temperature and pressure, movement of the casing due to subsidence are among the major drivers of cement debonding. Rock subsidence due to depletion is responsible for theshear failure. Due to rock movement, wellbore stresses get increased and thus cement-sheath integrity compromised [2]

Figure 2: Thermal fracturing effect on cement [2]

1.2 Chemistry of Cement

Portland cement is the most used cement in oil wells. It is also called; ordinary Portland cement (OPC) because of its manufacturing in the rotary kiln when ingredients are mixed in molten form at proper proportions. Some other types of cement are used in the wells when the condition of the well does not allow OPC. In OPC, compressive strength develops due to its hydration in which water and other compounds react with each other. This section highlights the information about cement manufacturing, its hydration and its classification for oil and gas applications.

1.2.1 Manufacturing of Portland cement

Clinkers are the main ingredient in Portland cement manufacturing process. It is the material that is produced by cement factory. It comprises of calcium silicates, calcium aluminates, and calcium aluminoferrrites. Gypsum, a form of calcium sulfate, is also added at the end to make the final product.

To produce clinkers for Portland cement, calcareous and argillaceous materials are necessary. Calcareous material contains lime and can be obtained from limestones, shell deposits, corals, precipitated CaCO3 and industrial processes. Argillaceous materials are usually yielded from shales, clays, marls, mudstones, volcanic ashes, fly ashes and blast furnace slag. These sources are necessary for silica, alumina and iron oxide production which is a vital part of OPC. Table 1 shows the mineralogical composition of Portland cement.

Table 1 Composition of Portland Cement

OXIDE COMPOSITION	CEMENT NOTATION	COMMON NAME	CONCENTRATION (WT%)
$3CaO.SiO_2$	C_3S	Alite	55-65
$2CaO.SiO_2$	C_2S	Belite	15-25
$3CaO.Al2O_3$	C_3A	Aluminate	8-14
$4CaO.Al_2O_3.Fe_2O_3$	C_4AF	Ferrite Phase	8-12

Cement manufacturing can be summarized in five steps:

1.2.1.1 Preparation of raw materials

Raw materials are converted into finely powdered state and are blended efficiently. A stable chemical composition is essential for kiln feed. This process can is done in either dry or wet conditions. Both grinding and blending are done with dry material in dry process whereaswater-based slurry is used in the wet process.

1.2.1.2 Heat treatment

It is performed in rotary kiln when the raw materials has already been passed through preheater. Solid material in the kiln slides down as the kiln is made inclined and rotates slowly at 1 to 4 RPM. Due to burning in kiln, large amount of greenhouse gasses gets produced which can be reduced by using alternates to fossil fuels or by improving kiln's fuel efficiency. Different reactions take place in kiln which eventually results in clinkers production. Figure 3 shows the process.

1.2.1.3 Cooling

Early and long-term compressive strength of cement depends upon how the clinkers are cooled after heat treatment. Slowcooling rate result in cement which less hydraulicallyactive having high early strength but weak in long term. Too fast cooling gives opposite results. The optimum cooling process initially lowers the temperature to 1250degC and then rapidly cools it at rateof 18 to 20 °C/min.

1.2.1.4 Grinding

Clinkers are then grinded with gypsum (a form of calcium sulfate) which is used to increase the setting time of the cement. Lack or absence of gypsum results in a phenomenon of flash setting which occurs due to the formation of hydrocalumite. Too much hemihydrated calcium sulfate results in the gypsum precipitation which further leads to early setting of cement called false setting [3]. Tubular mills are used to ground the clinkers which make use of hard steel balls.

1.2.1.5 Storage

Quality of Portland cement can be maintained if stored in dry environment. Moisture may induce certain properties which result in low strength after setting. Therefore, the humidity should be monitored and kept as low as possible in the warehouse.

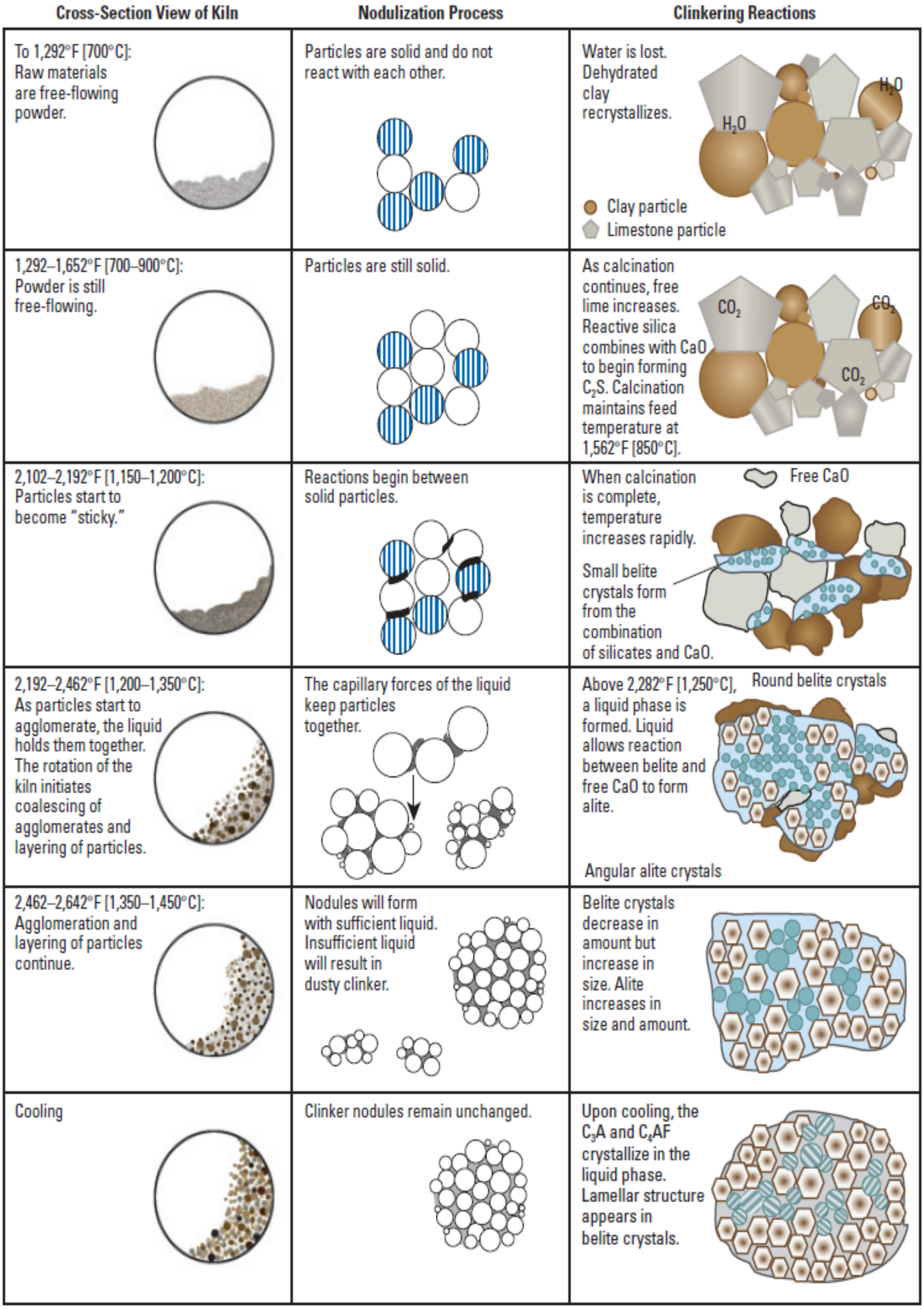

Figure 3: Production of Clinkers (Raw Feed to Finished Product) [2]

1.2.2 Clinker Hydration Process

All the material in Portland cement are anhydrous. Therefore, different hydrated compounds are formed when water is added to it. Individual phases of clinkers are analyzedin order to understand the hydration process. Each phase in Portland cement produce different hydration results after following its own hydration kinetics.

1.2.2.1 Silicate Phase.

Portland cement mostly comprises of silicate phases (almost 80%). C3S and C2S are two silicate phases in OPC. Chemical reaction converts them into calcium silicate hydrate and calcium hydroxide.

$$2C_3S \rightarrow C_3S_2H_3 + 3CH \quad (1)$$
$$2C_2S + 4H \rightarrow C_3S_2H_3 + CH \quad (2)$$

After developing initial hydration, silicate phase enter a stage of low hydration rate called induction period. After this stage, C3S hydration rate leaves behind the hydration of C2S and result in early strength development. C2S hydration affects the strength of final hardened cement. The hydration process for the silicates is similar. Typically C3S follows five stages during its hydration that is an exothermic process. These stagesare defined by the results from thermogram (figure 4) [2].

I. Preinduction period
II. Induction period
III. Acceleration period
IV. Deceleration period
V. Diffusion period

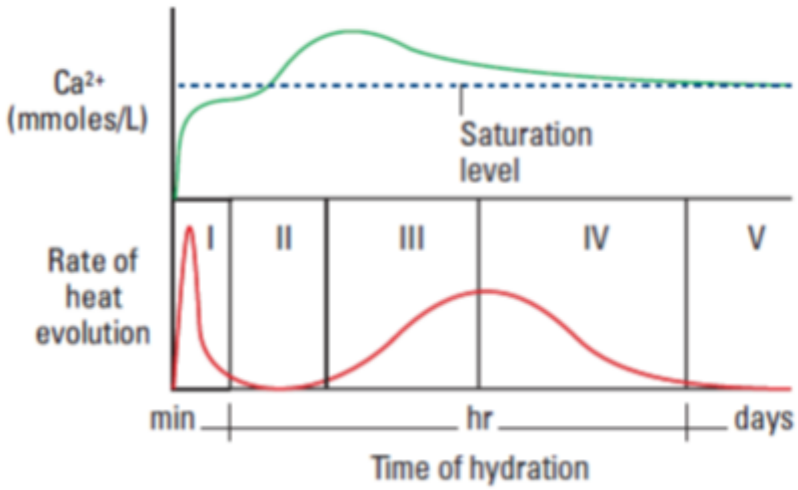

Figure 4: Evolution of Heat vs Time of Hydration [2]

1.2.2.2 Aluminate Phase

Rheological properties and early cement strength depends on the hydration of aluminate phases. At short hydration times, aluminate phase like C3A is the most reactive one. Gypsum added in the grinding phase of OPC manufacturing also take part in the reaction. Figure 5shows the reaction kinetics for clinkers materials.

$$2C_3A + 27H \rightarrow C_2AH_8 + C_4AH_{19} \tag{3}$$

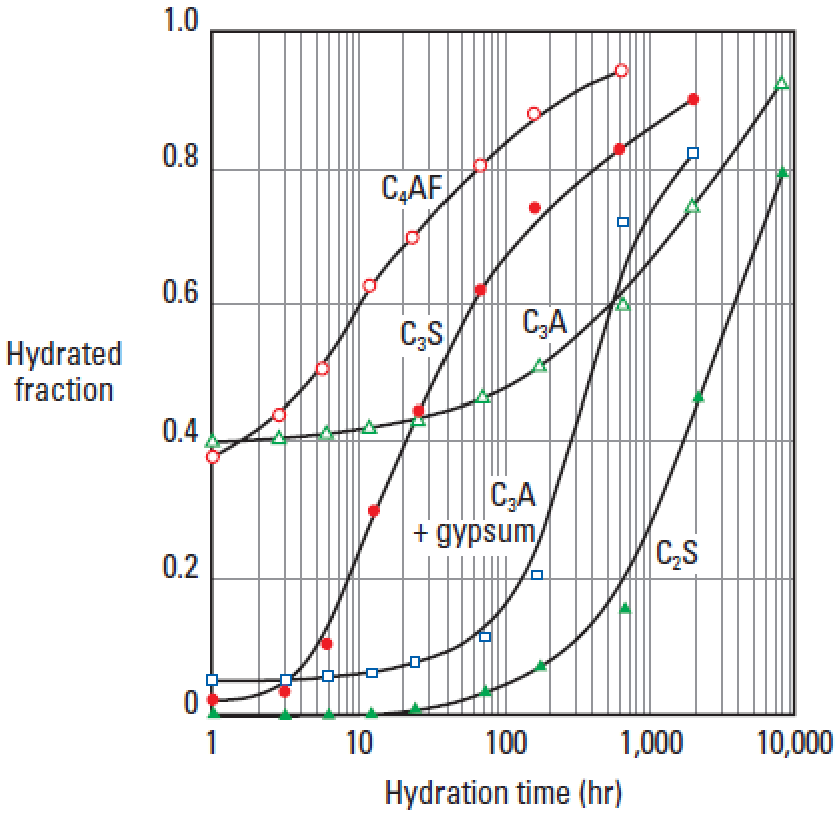

Figure 5: Typical Clinkers' Hydration Kinetics at the surrounding temperature [2]

1.2.3 Hydration of Portland cements

When the Portland cement is subjected to hydration, different chemical reaction takes place simultaneously. These reactions consume clinker components, water and calcium sulfate (usually gypsum). As a result of chemical changes, a thick cement slurry is formed which becomes hard afterward. Figures; 6 and 7 show schematic of cement hydration and its thermogramrespectively. Since Portland cement mostly consists of C_3S, therefore, hydration of Portland cement is usually modeled through the hydration of C_3S. but it can introduce inaccuracy in the model as the hydration of Portland cement is not a simple process because of overlapping reactions during hydration. For instance, the hydration of C3A is influenced by hydration of C3S. Purity of clinker materials also affects the complexity of reaction.

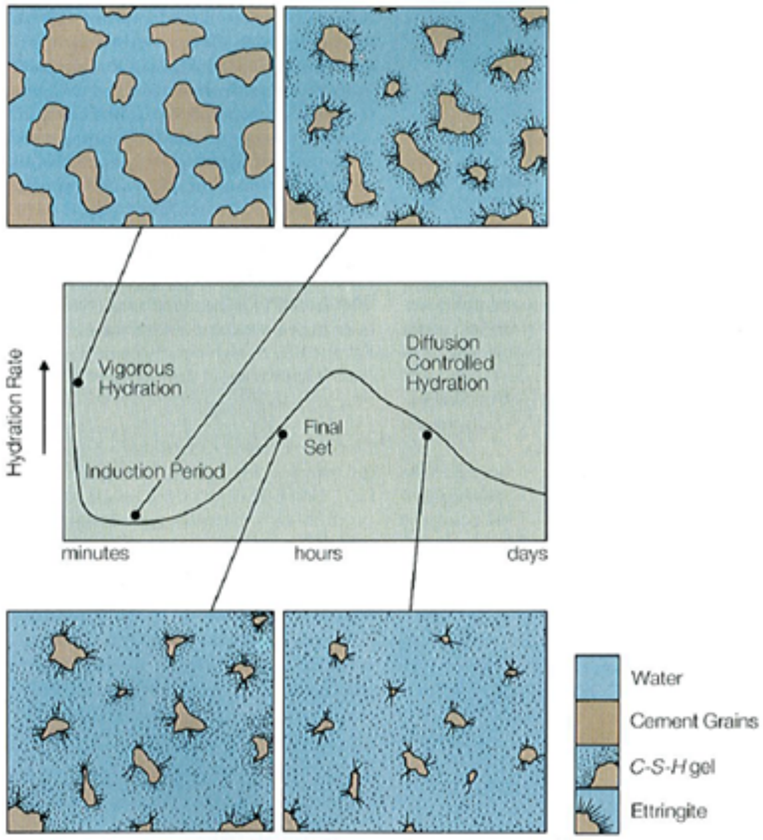

Figure 6: Cement Hydration Process [4]

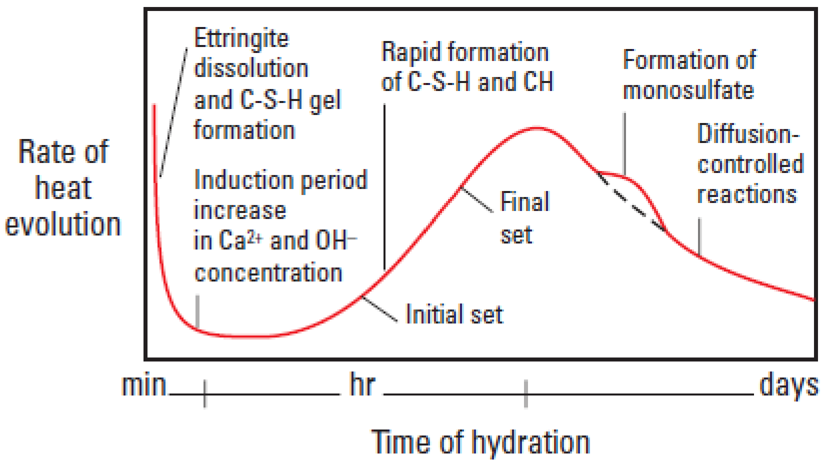

Figure 7: Schematic of Hydration Process of Portland Cement [2]

One of the most important factors affecting cement hydration is temperature. High temperature makes the hydration process faster. Figure 8 shows the hydration curves for different set of temperature. At elevated temperature, induction and setting periods' durations become shorter with high rate of hydration during setting period. But the strength and degree of hydration get reduced on extended curing. There are some other factors which affects the hydration process such as aging, quantity of calcium sulfate, alkali concentrations, cement fineness.

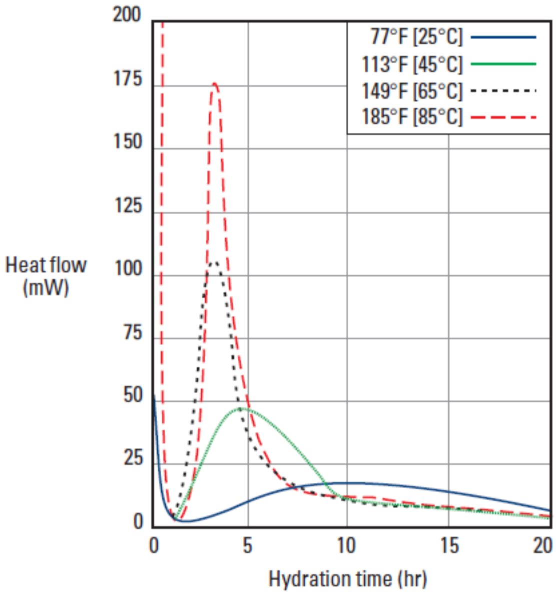

Figure 8: Temperature Effect on Hydration of Class G Cement [2]

1.3 Classification of Portland cements

Portland cementsare classified by different standardized organizations based on area of application. Oil industry follows API Classification which was also adopted by ISO. API-ISO classification system of Portland cement has eight classes; named A to H. the arrangement is done based on the downhole conditions and depth of placement. Sulfate resistance of some classes are also specified as O (ordinary), MSR (Moderate Sulfate Resistance) and HSR (High Sulfate Resistance).

1.3.1 Class A, B and C:

Grinding of Portland cement clinkers yield A, B and C classes of cement which usually comprises of calcium silicate and also contains calcium sulfate.

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Class A: It is used in oil wells without having any special properties. The sulfate resistance requirement is ordinary for this type of cement.
Class B: It is selected when sulfate resistance requirement is either moderate or high.
Class C: It is chosen for the wells requiring high early strength. All types of sulfate resistance are available with this class.

1.3.2 Class D, E and F:

These classes find its application in the wells having relatively higher temperature and pressure. Different set modifying agents are added during manufacturing process to the clinkers. Available sulfate resistance for these classes is MSR and HSR. They are also termed as retarded cement as the quantity of faster hydration components are being reduced as well as cement grain size is also larger. Due to the development of retarder as an additive, very few wells are now using these classes.

1.3.3 Classes G and H:

These types of cement are obtained by portland cement grinding and it compose of calcium silicate with at least one type of calcium sulfate without any further addition. Available grade with these type of cement are MSR and HSR and they are mostly used in oil industry. Additives like accelerators and retarders can work effectively in these classes.

1.4 Cement Additives

The downhole cementing conditions are very important to know in order to perform a good cementing job. From permafrost to high temperature, Portland cement system is subjected to severe thermal conditions in the wells. Shallow and deeper wells also exposed the well cement to extreme conditions of pressure. Formation fluid composition and rock strength also affects the performance of cement in the well. The purpose of cement additives is to make the cement ideal for the downhole condition from well to well so that well integrity cannot be compromised in the whole life of the well.

Cement additives are categorizedinto seven major types.

1.4.1 Accelerators

It fastens the initial stages of hydration and reduce the setting time of cement. Shallow and low-temperature wells are the potential application areas for accelerators. It also cancels the delay effect caused by other additives. Salts of chloride such as $CaCl_2$ are mostly used as accelerators. Carbonates, aluminates, silicates, sulfates and alkaline bases can also be used in cement to have accelerating effect.

The accelerating effect of calcium chloride is still a debatable issue. Some argue that it accelerates the hydration process by allowing more access to water towards the anhydrous surfaces. it does so by improving the permeability of C-S-H gel which builds around silicate grain. Usually $CaCl_2$ is added to the cement in the concentration range of 2 to 4 % by weight of cement (BWOC). Figure 9 shows the effect of concentration of $CaCl_2$ on thickening time (top) as well as on development of compressive strength (bottom).

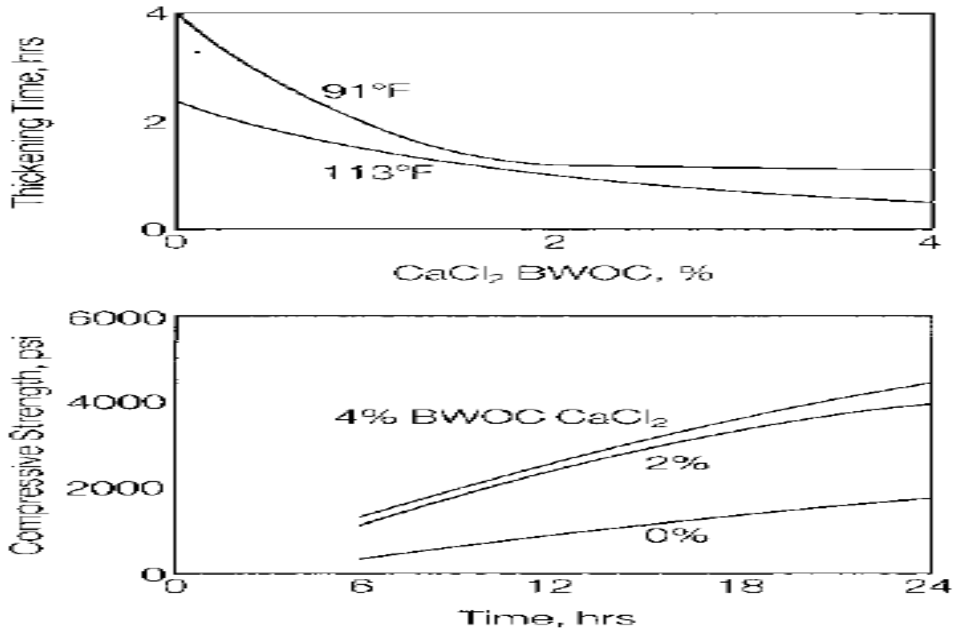


Figure 9: Effect of concentration of CaCl2 on thickening time and on development of compressive strength [4]

1.4.2 Retarder

In hot and deep wells, pumping time plays an important role as the cement has to be placed at its designated place before it sets. The only way to do so is to reduce the rate of hydration and delay the setting time. This is accomplished in oil well-cementing industry by the use of retarders.

Wood pulp is the main source to derive retarders. Salts of sodium and calcium from lignosulfonate acids are the main constituents of these retarders. It works by making the surface of C-S-H gel hydrophobic enough so that the induction period gets increased. Typically they are added at 0.1-1.5% BWOC and can work up to downhole temperature of 122^0C. The temperature range (up to 315^0C) can be improved by adding borax to them. Figure 10 shows the effect of the retarder on thickening time. Other retardersare also used in the industry for example hydroxycarboxylic acids, saccharides, cellulose derivatives, organophosphates and few inorganic compounds.

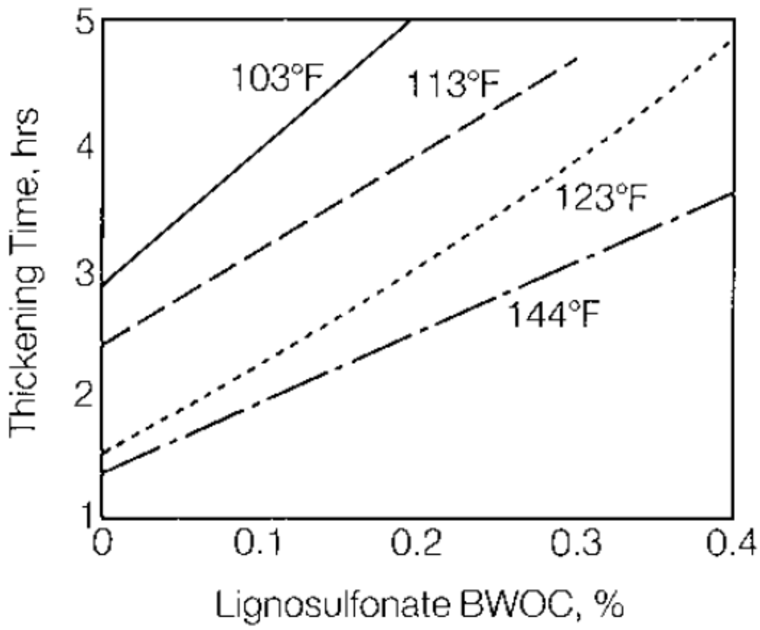


Figure 10: Effect of Lignosulfonate BWOC on cement thickening time [4]

1.4.3 Extenders

In order to reduce the hydrostatic head of cement on formation, slurry density has to be decreased. This is accomplished by using extenders in the slurry. Extenders also improves the yield of slurry.Water based, low-density aggregates and gases can be used as extenders in the slurry depending upon the objective high yield orlow head on formation. Figure 11 summarizes some extenders used in the industry.

Extender	Range of Slurry Slurry Densities Obtainable (lbm/gal) 6 – 11 – 16	Performance Features and Other Benefits
Bentonite	11.5 – 15	Assists fluid-loss control
Fly ashes	13.1 – 14.1	Resist corrosive fluids
Sodium silicates	11.1 – 14.5	Available in solid or liquid form; effective at low concentrations; ideal when mixing slurry with seawater
Microspheres	8.5 – 15	Good compressive strength, low permeability, thermal stability, and insulating properties
Foamed cement	6 – 15	Good compressive strength and low permeability

Figure 11: Common extenders in Industry

The effect of three types of extenders in cement slurry is shown in figure 12. Bentonite is the most common water-based extenders which swells drastically in water. It decreases the density at the cost of low compressive strength (right). Microspheres are the gas-filled beads having specific gravity as small as 0.2 and are used as second type of extender in the industry. It reduces the density without compromising compressive strength as the water is not added. Some gases such as air, nitrogen are also used as extenders to reduce the density. These types of cement are termed as foamed cement.

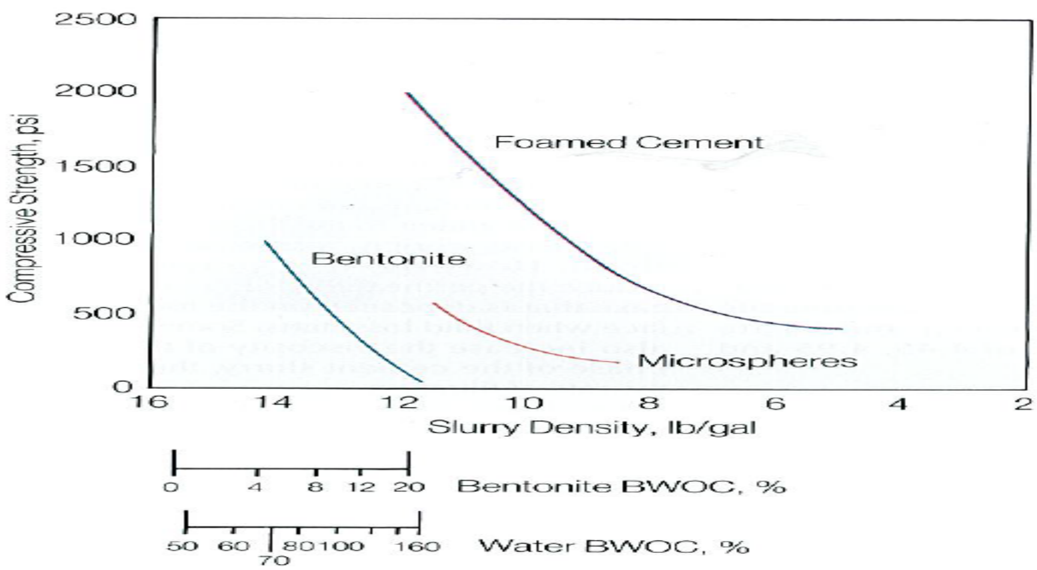


Figure 12: Effect of Foamed Cement, Microspheres and Bentonite on compressive strength [4]

1.4.4 Weighting Materials

High-pressure wells require high density for both drilling fluid as well as cement slurry. The common way to increase density is to reduce the amount of water. But it reduces the setting time of the cement as well making it difficult to pump. In cements, several additives are available to increase the density such as hematite (Fe_2O_3),ilmenite ($FeTiO_3$) and barite ($BaSO_4$). Figure 13 shows slurry density as a function of weighting agent concentration.

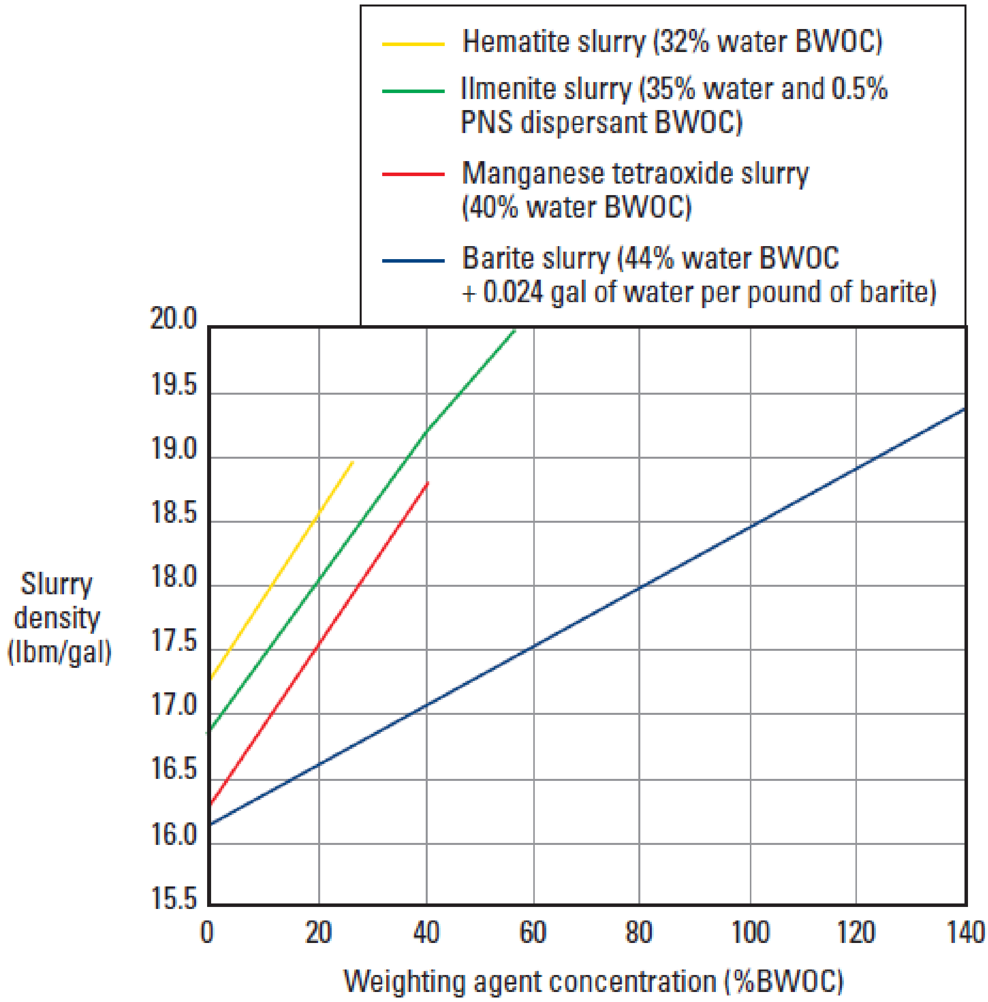


Figure 13: Slurry density vs Weighting agent concentration [2]

1.4.5 Dispersants

Turbulent flow with slurry is often needed to remove the drilling mud effectively from the well during cementing operations. This is achieved by adding dispersants so that it control the rheology and increase turbulence effect at low pumping rates. Addition of dispersant also reduces the amount of water in cement without affecting the available pumping time.

Positive charges of cement get neutralized by the dispersants. If added at right amount, it can enhance the homogeneity of cement as well as lower the permeability. Large amount of dispersant creates free water and cause phase separation. The most efficient dispersant is polynapthalenesulfonate (PNS). Other sulfonate can also be used as dispersants such as polymelaminesulfonate, polystyrene sulfonate.

1.4.6 Fluid Loss Control Agents

Fluid loss is a process in which liquid phase of slurry get into the formation leaving behind the solid particles. Due to this, the properties of cement slurry is not remained as per the design. Severe fluid loss can made the cement slurry unpumpable. Normally the fluid loss rate of neat cement slurry is 1500ml/30min which quite higher than the usual requirement of 50ml/30min. thus fluid loss control agent find its application in cement industry.

These agents reduce the permeability of filter cake formed by the cement solids in the slurry at the formation interface. Another purpose of fluid loss control agents is to increase the viscosity of aqueous phase making it harder to penetrate into the formation. These additives are classified into two types; designated as water soluble polymers and solid particulate. Water soluble polymers like HEC works by increasing the aqueous phase viscosity and reducing filter cake permeability, cellulose derivatives are the most commonly used in the industry. Figure 14 illustrates the effect of addition of HEC as fluid loss additive in cement slurry. Solid particulates such as bentonite, microsilica, PVA (poly vinylalcohol)etccause a decrease in filter cake permeability by entering into the filter cake.

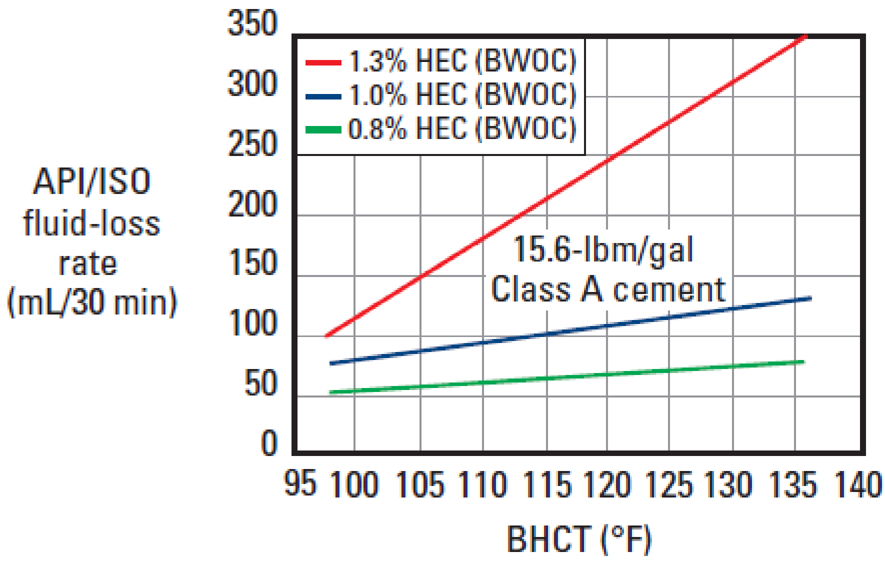


Figure 14: HEC Performance as Fluid Loss Additive [2]

1.4.7 Other Additives

There are numerous material that are added to the cement slurry to improve performance of certain areas such as lost circulation, durability of cement, foaming etc.

1.5 Cement Properties and Measurements

This section summarizes the major properties of cement slurry and their measurement techniques. API RP 10B explains the operational procedures for preparing cement slurries for the well in laboratory. A two-speed mixer of propeller type (Figure 15)is typically used to prepare 600mL of slurry by making use of 4000RPM and 12000RPM rotation speed for 15s and 35s respectively. It will ensure adequate mixing of all dry materials. Liquid additives are added to cement after dispersing them into mix water. Field mixing (either fly or batch) should be kept in mind so that slurry in the lab should be exposed to relevant time and temperature conditions.

Figure 15: Common Laboratory Mixers [2]

1.5.1 Slurry Density

API RP 10B explains the procedure to measure the slurry density through pressurized mud balance (figure 16). The cup is filled with the slurry and then closed by screwing the pressure cap on its top. Air bubbles are removed fro the cup by inserting slurry through pressurizing plunger into the cup. Density is then determined by placing the cup on fulcrum and sliding the weight to balance both the sides.

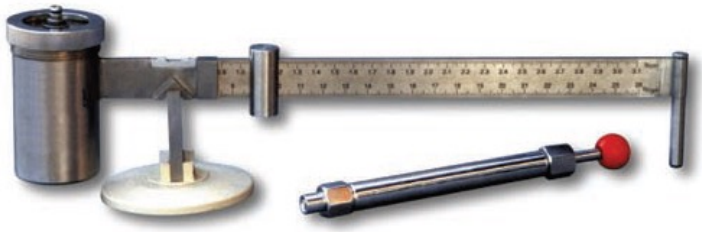


Figure 16: Pressurized Mud Balance [2]

1.5.2 Thickening Time

It determines how long the slurry remains in a pumpable state. Pressurized consistometer (figue17) is used to measure the consistency of slurry when it is put in rotating cup at the conditions similar to that of the wellbore. Both high and low high temperature and pressure conditions can be applied to test slurry. Consistency is measured in Bearden units (B_C) with 100 B_C corresponds to end of thickening time and 70B_C to be maximum time of being in pumpable condition. Figure 18 shows result of cement slurry from consistometer. Atmospheric consistometerare also used for low-temperature cement systems.

Figure 17: Pressurized Consistometer [2]

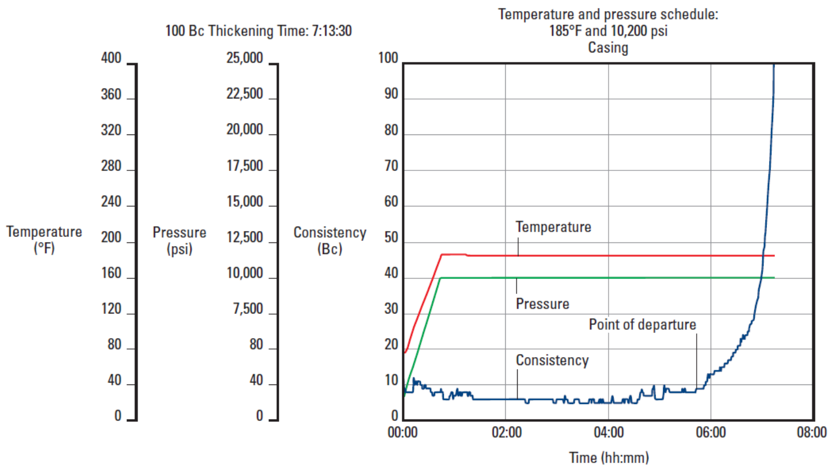


Figure 18: Thickening time test results [2]

1.5.3 Fluid Loss

The quantification of fluid loss of cement slurry is done through filter press cell (figure 19). The cell measure the static fluid loss by putting the slurry under differential pressure and forcing it to pass through filter medium in a specificperiod of time (usually 30 minutes). Tests can be performed at high pressure and high-temperature conditions if HPHT filter press is used.

Figure 19: Filter Press with its components [2]

1.5.4 Strength

Compressive and sonic strengths are the two types of strength that are being measured in the laboratory for the set cement. Compressive strength is determined by hydraulic press containing two set cement cubes having known cross-sectional areas. Load at which the samples get failed is then converted into compressive strength. Figure 20 shows atypical hydraulic press.

Sonic strength of cement is measured by ultrasonic cement analyzer (UCA) which works on the principle of determining the travel time of sound energy through the sample as it cures inside the analyzer (figure 21). The travel time is then converted into strength by computer programs using empirical correlations which depend upon type of cement system.

Figure 20: Hydraulic Press which measures the compressive strength of cement [2]

Figure 21: Ultra Sonic Cement Analyzer (UCA) [2]

1.5.5 Permeability

As zonal isolation heavily rely on the permeability of cement in the wellbore, it is vital to measure the permeability of set cement in the laboratory so that necessary changes can be made prior to the execution of cement operation. Different parameters are available to quantify set cement permeability depending upon the fluid being used during measurement such as water, gas etc. Figure 22 presents Hasler sleeve type holder for measuring permeability through water.

Figure 22: Permeameter to measure water permeability (Hasler sleeve type holder) [2]

1.5.6 Rheology

Cement rheology is very important to know as it determines flow properties and friction pressure. Rheology of cement slurry is studied by measuring shear stresses at varying shear rates in coaxial cylinder rotational viscosmeter. Couette type viscometer is shown in figure 23. The slurry is first prepared as per API guidelines and then preconditioned in consistometer before placing it in viscometer. Once the preconditioning is done, preheated cup of viscometer is filled by the slurry and the test begins at desired temperature.

Figure 23: Couette-type rotational viscometer [2]

1.5.7 Expansion and Shrinkage

Different equipments are used to measure the expansion and shrinkage behavior of cement slurry as it cures. These include membrane test, cylindrical sleeve, annular ring expansion mold and cement hydration analyzer (CHA). Membrane test is aclosed system in which impermeable conditions are created and bulk expansion and bulk shrinkage isbeing measured. Cylindrical sleeve test determines expansion by giving the system access to water (open system). Annular ring method evaluates the linear expansion of cement when it is exposed to water during its curing. Figure 24 illustrates a diagram of CHA showing how the gas is being injected into the sample slurry during its setting. Due to shrinking effect of slurry, certain volume of injected gas is used to keep the constant pressure. Both gas (closed system) and water (open system) can be used as injected fluid.

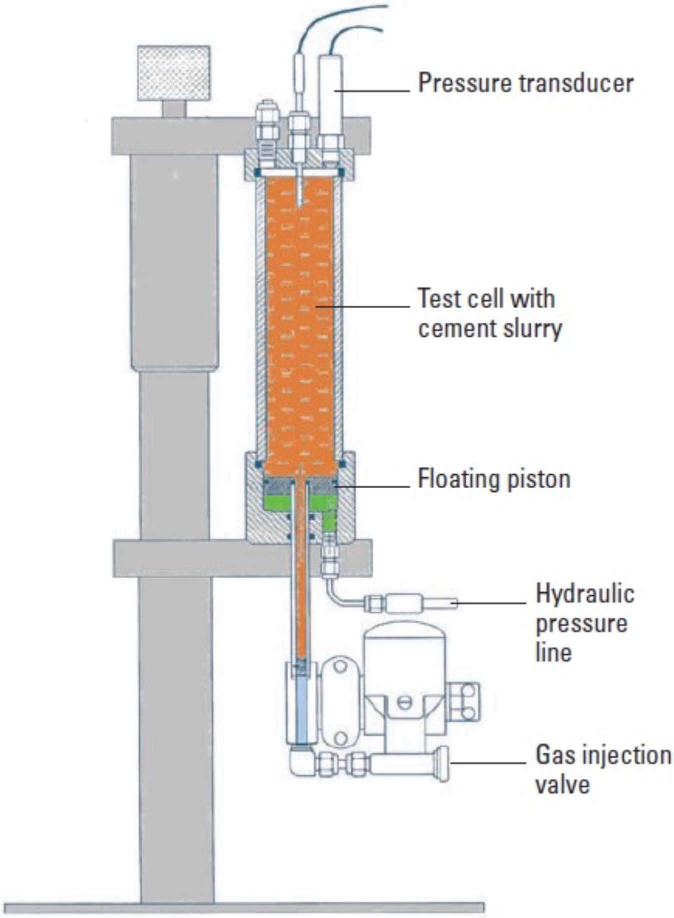


Figure 24: Schematic of cement hydration analyzer [2]

1.6 Cement Placement Technique

Usuallycement is pumped down from inside of the casing to all the way up in the annulus. In some cases where lost circulation zones exist near the shoe, cement can be pumped through annulus so that upper zones can be isolated from bottom. Another method which is usually adopted for large diameter casing is to pump cement through drill pipe. An alternate to this method is grouting technique in which a small diameter pipe is used inside the annulus to pump the slurry down. Cementing can also be performed in single as well as multiple stages depending upon the strength of formation and other factors. This section covers major cement placement techniques which are adopted in the field for different type of applications.

1.6.1 Inner String Cementing

In this method, stab-in float shoe is being made part of casing and run in the hole along with casing and other casing hardware. It has profile in which drill pipe stab-in stinger can stab or screw so that a proper seal can be established. After running the casing, drilling mud is circulated through drill pipe and its annulus with casing before stabbingin. after the stringer get stab-in properly in the float shoe and circulation also confirm about it, cement slurry is prepared and pumped down through drill pipe so that it can rise inside the annulus until it reach the surface. Figure 25 gives an overview of the method.

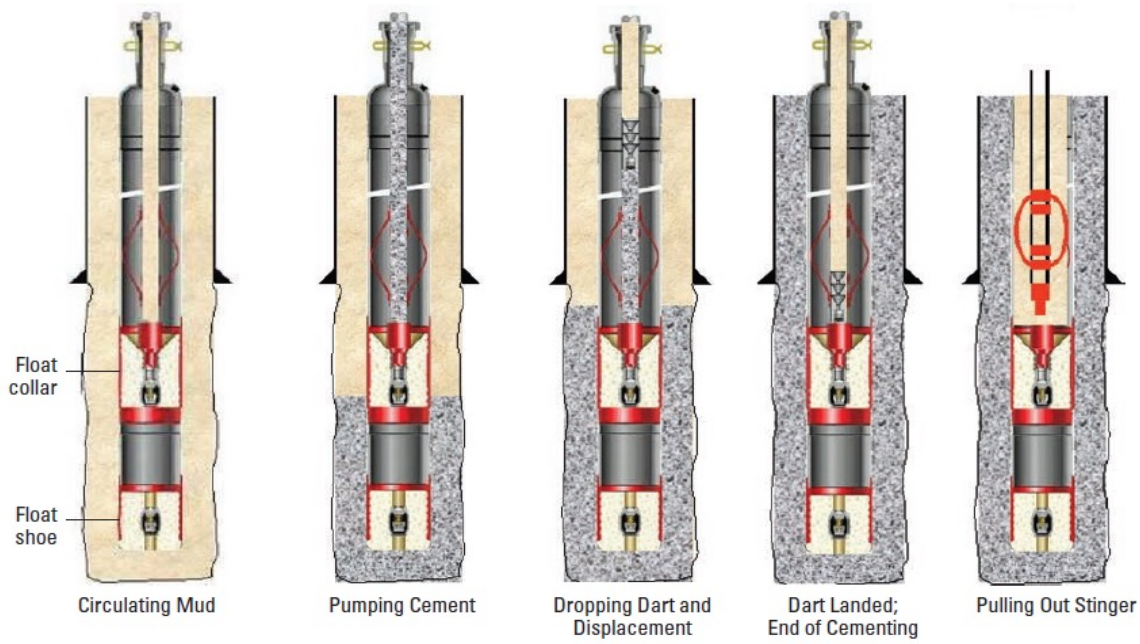


Figure 25: Inner String Cementing through drillpipe cementing [2]

Elimination of possibility of overdisplacement, minimal cement contamination, avoidance of large diameter cement heads and less dependence on hole volume are among the key benefits of drill pipe stab-in cementing. One of the greatest risk involve with this type of cement placement technique is casing collapse.

1.6.2 Top up Cementing

Top up cementing, also called grouting, is used when the cement is not returned to the surface during displacement due to the slurry losses in weak formation. Cement is usually pumped down through small diameter tubing (1-7/8 in) which is placed as deep as possible between casing and open-hole. When cement starts to come to the surface, surface lines as well as tubing are flushed with water and tubing is pulled out of the annulus (figure 26)

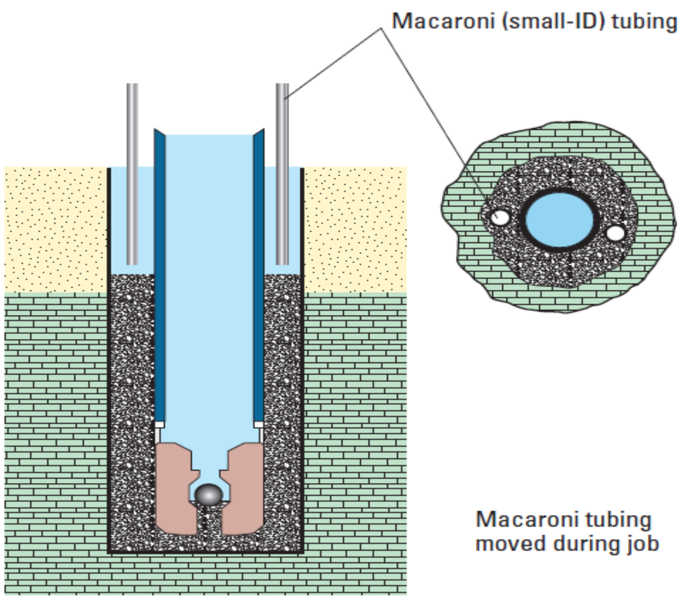


Figure 26: Grouting (top-up cementing) [2]

1.6.3 Single stage Cementing

Single stage cementing is a technique to conduct primary cementing when the formation is strong enough to support the downhole pressure caused by the cement column inside the annulus. It is nowadays also used to carry out cementing in weak formation using advanced cementing system such as foamed cement, low-densitycements etc. In this method, casing is first placed inside the well and mud conditioning is carried out. It is always recommended to have both in and out mud weights equal and fluid rheology should be maintained towards the lower side. Cementing head is then connectedwith the casing with both bottom and top plug loaded in it. Spacer is being pumped followed by dropping the bottom plug. The purpose of spaceris discussed in section 2.7.1. Calculated volume of cement slurry is then pumped which is followed by topplug. After top plug, mud displacement begins and it is doneuntil the top plugreach the float equipment which is confirmed by the increase in surface pressure. Figure 27 shows a brief schematic of the whole single stage cementing process [5].

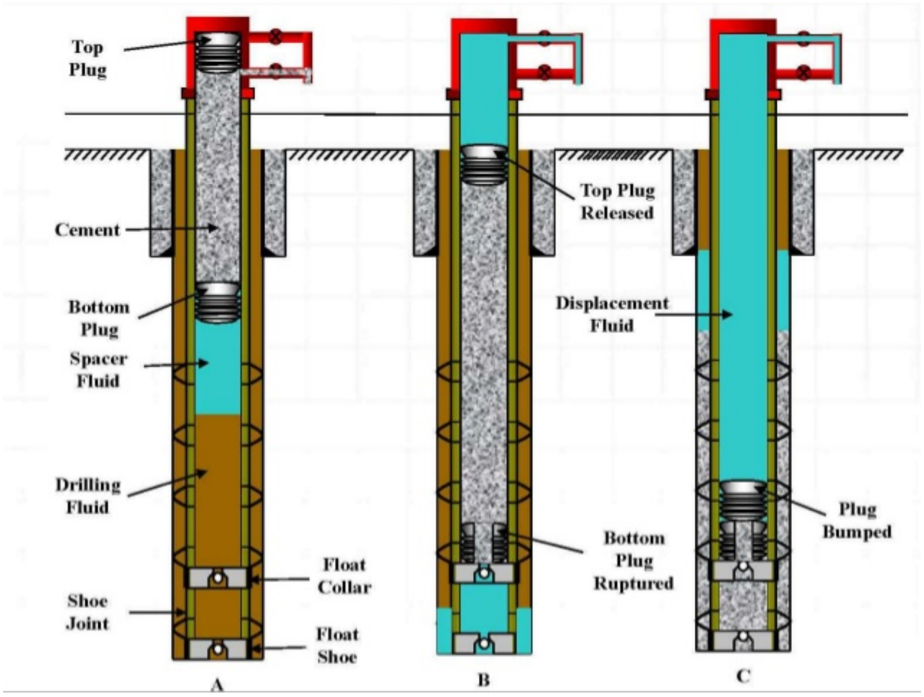


Figure 27: Schematic of single stage cementing [5]

1.6.4 Multi-stage cementing

Multiple stage cementing finds its application in the scenarios when,
Requirement of cement is not mandatory between the intervals which are widely separated.
High cement density is needed to isolate upper zones
Weak formations do not allow long cement column to be used.
Figure 28 illustrates conventional multi-stage cementing operation. The casing hardware consists of an additional tool called stage collar. Stage collar is primary tool in multi-stage cementing which allows to isolate everything below it once the first stage cementing get completed by normal cementing technique. It can be operated either mechanically by dropping the opening bomb or hydraulically by pressurizing the casing. The cement is then circulated through the ports of stage collar and a closing plug is dropped followed by mud displacement.

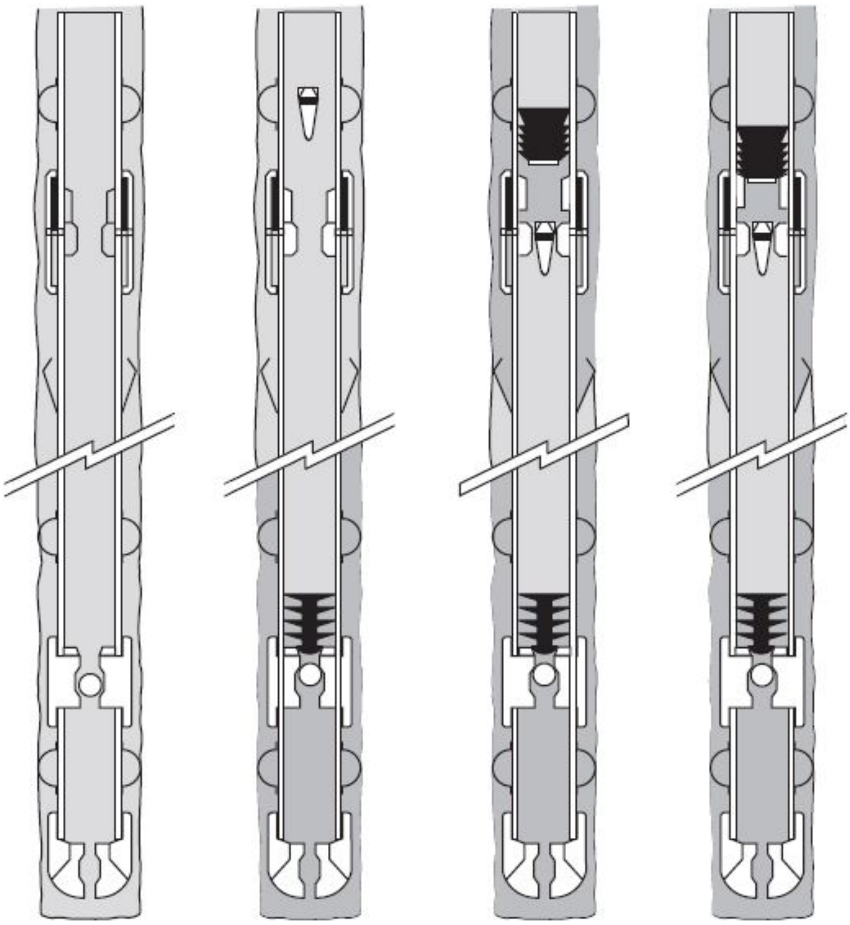


Figure 28: Illustration of multi-stage cementing [6]

1.6.5 Liner cementing

Liner along with linger hanger is run on drill pipe and always kept in tension. Liner consists of another equipment in addition to float, called landing collar. The requirement for mud conditioning is similar for liner as well. Liner cementingconsists of pump-downdart and liner wiper plug. At first, the spacer and cement are pumped down followed by dropping the pump-down dart from the liner cementing head connected to the drill pipe on surface. On its way down, drill pipe dart engages with liner wiper plug and then both the plugs begins to displace the slurry until they reach the landing collar. Liner cementing operation is shown in figure 29.

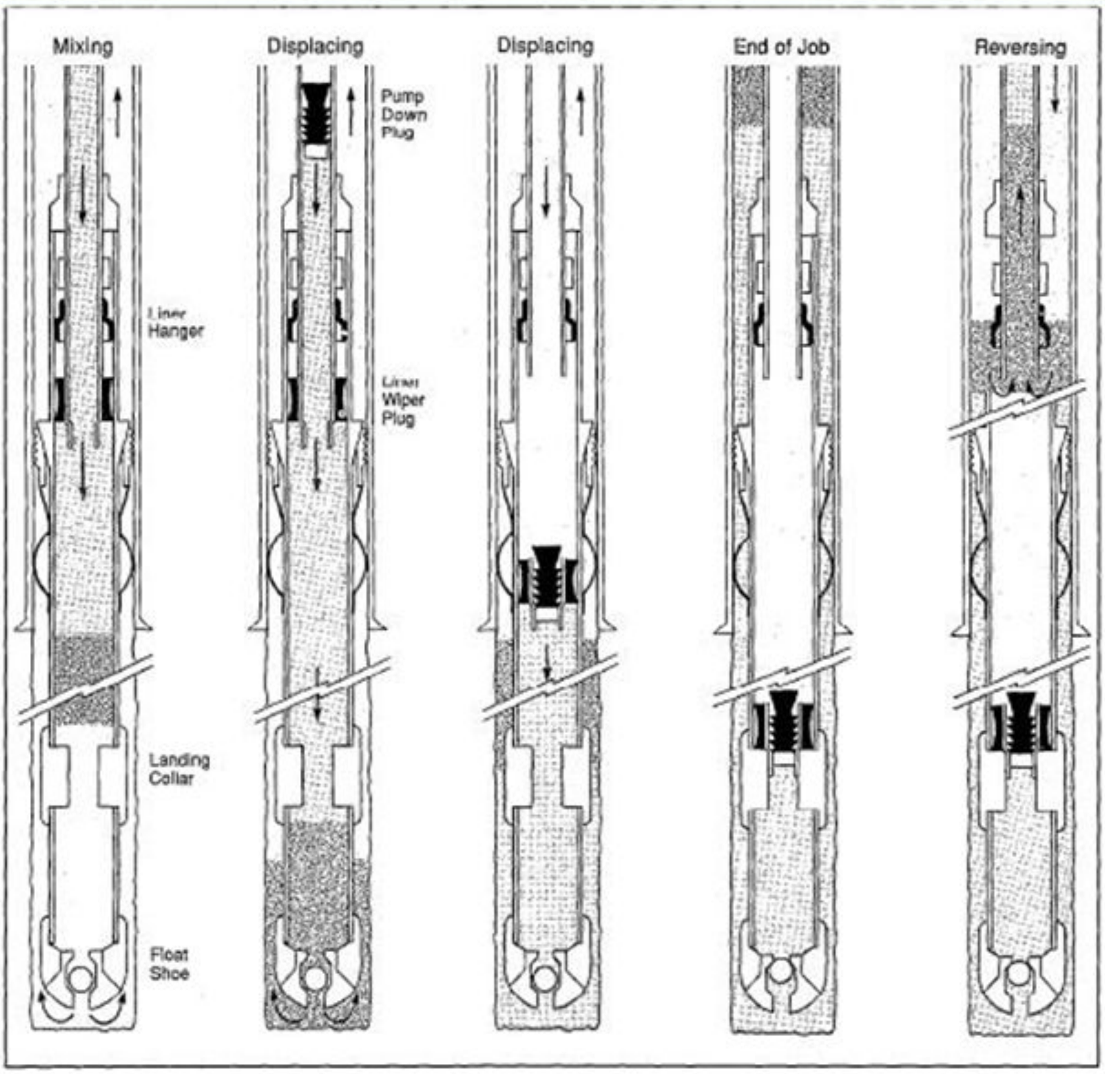


Figure 29: Schematic of Liner cementing process [7]

1.6.6 Remedial cementing

It encompasses all the operation in which cement slurry is being employedin order to cure well problems. The requirement of remedial cementing can arise in any phase of the well from construction to production and abandonment. The removal of defects in primary cementing jobs, maintaining integrity of well bore, restoration of production, repair of corroded tubular and placement of long-term isolation barrier before leaving the wellare among the major remedial cementing operation. This section will through light on issues that can be resolved through remedial jobs as well as two major classes of remedial cementing, designated as plug cementing and squeeze cementing.

1.6.6.1 Application areas for remedial cementing

Various problems can arise related to well integrity and zonal isolation during the life of the well. Remedial cementing can be used as procedure to overcome some of them (Table 2). Few of them are listed below.

A. Lost Circulation
Although LCMs are usually pumped to cure loss circulation problems but sometimes the losses cannot be controlled by them due to very weak nature of formation. Cement plugs are then placed with small amount of cement being squeezed into the formation to strengthen the rock.

B. Sidetrack
Cement plug, known as kick off plug is placedin order to deviate from existing profile as part of plan or due to restriction in the way of the well like fish.

C. Protective plugs
Before testing any formation, cement plug should be placed across the weak formation in the open hole so that it can be isolated from downhole pressures.

D. Primary cementing job defects
Due to multiple reasons, defects can be present in the cement placed in the primary cementing operation. Once the defects get detected, a squeeze cementing job can be carried and an evaluation of the job can be donein order to confirm the removal of defect.

E. Packer and casing leaks
Due to corrosion, casing and packer can develop leaks which can lead to further problems during production. Cement plugs can be placed around the leak points after their confirmation.

F. Perforation Closure
Unexpected GOR and water cut can be controlled by closing the perforation at right place. A low-pressure squeeze cementing job can be applied to close the unwanted perforation.

G. Well abandonment
Operators have to place cement plugs before leaving the well in order to comply government regulations. These plugs are planned carefully so that it can withstand the downhole condition forever.

Table 2 Application Areas of Plug and Squeeze Cementing [2]

PLUG CEMENTING	SQUEEZE CEMENTING
Directional Drilling Initiation	Cement job repairs
Sidetracking	Sealing lost circulation zones
Sealing of lost circulation zone	Gas/water producing zones' isolation
Anchoring provision for open hole test	Elimination of water intrusion
Low-pressure formation protection	Abandonment of depleted zone
Isolating zone of depletion	Casing leaks repair
Plug and Abandonment	Directing injection towards a zone

1.6.6.2 Plug Cementing

Cement plug can be placed in the well by using several methods. Balance cement plug and dump bailer method are extensively used in oil field. A brief overview of these methods is as follows,

1. Balanced Cement Plug

It is the commonly used technique in plug cementing while carrying out remedial jobs. In this method, drill pipe or cement string is placed at the plug setting depth and calculated amount of slurry is being pumped. Often spacer and washers are used to avoid contamination of slurry with mud (Figure 30). The slurry is then displaced by the mud so that height of cement inside and outside the pipe is similar (balanced condition). Pipe is pulled out from the unset cement and is being reverse circulated to ensure that there is no excess cement in the pipe.

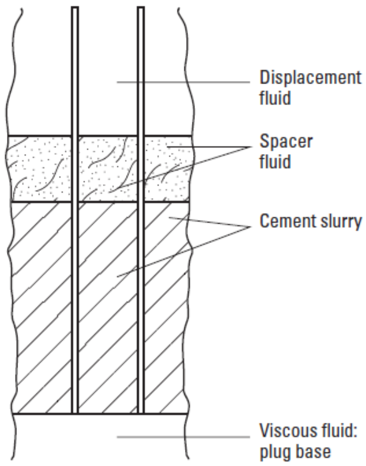


Figure 30: Balanced plug cementing [2]

2. Dump Bailer Method

Dump Bailer Method is the technique of placing cement plug in which cement slurry is loweredin the well by putting it inside a vessel called dump bailer. A cable enables the bailer to reach the bottom and placed the cement slurry on top of already installed mechanical foundation such as bridge plug. It allows knowing exactly about the depth of plug.

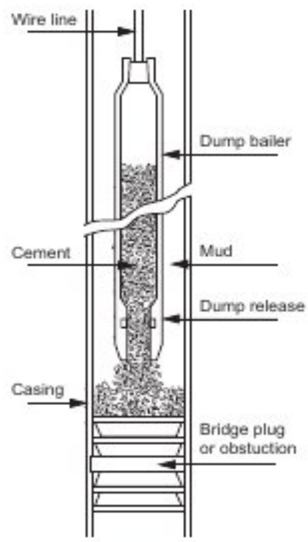


Figure 31: Dump Bailer Method [8]

Other methods can also be adopted to carry out plugginjob such as two plug method, flexible bags, coiled tubing method, umbrella-shapedmembranesand inflatable packers.

1.6.6.3 Squeeze Cementing

Squeeze cementing consists of all the remedial cementing operations in which the slurry is forced into a particular location for instance perforations and channels, so that zonal isolation can be attained. Figure xx shows the potential application areas where squeeze cementing can be performed. This section gives an insight into different approaches that can be adopted during squeeze cementing.

1. Low and high-pressure squeeze method

Low and high-pressure squeeze are two fundamental classes of squeeze jobs. In low-pressure squeeze, downhole pressure during the job never increases the fracture pressure of the formation. The objective is to place the cement filtercake in the perforation cavities and voids. As the slurry is not designed to be pumped inside the formation therefore, the requirement of slurry volume is very low. The mandatory requirement of lowpressure squeeze is that the perforations should be cleaned from mud solids and other debris.
In high-pressure squeeze, the bottom hole pressure during the squeeze job is maintained above the fracture strength so that channels can either be created or enlarged so that proper cement placement can be done. This type of squeeze can also be applicable to the areas where it is not possible to remove the debris ahead of the slurry. The direction of fracture created as a result of this process is very difficult to control.

2. Running and hesitation squeeze method

Running and hesitation squeeze methods are othertypes of squeeze jobs. In running squeeze job, slurry is continuously pumped and a squeeze pressure is achieved which can be either higher or lower than formation fracture pressure. This pressure is maintained at this level for several minutes. In hesitation technique, pressure is applied by pumping the slurry at 0.5 bbl/min. The application of pressure is separated by specific time interval so that filtrate can be lost to the formation (figure 32). Less amount of slurry is needed for this method.

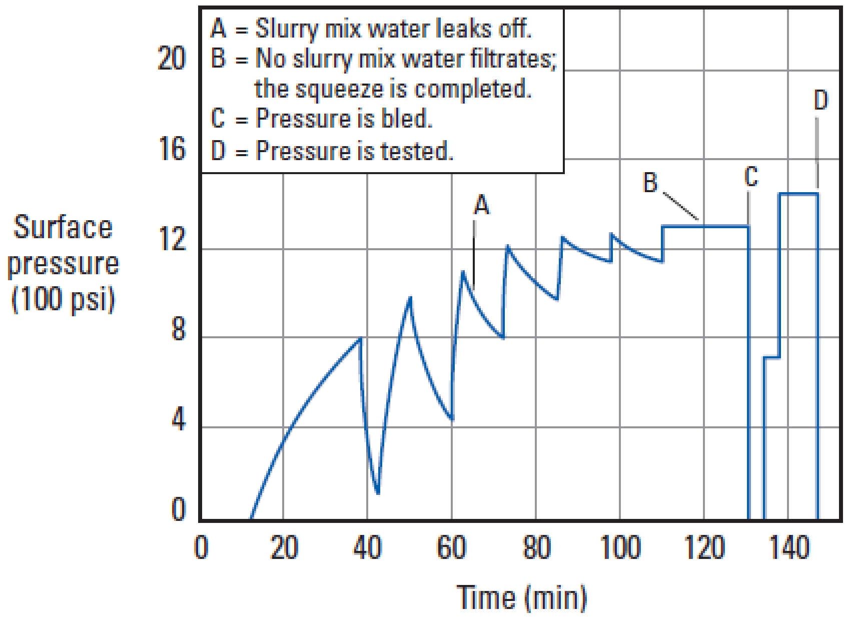


Figure 32: Pressure Response during Hesitation Squeeze [2]

3. Bradenhead and squeeze tool method

In bradenhead squeeze technique, cement is spotted at the desired location through tubing for instance in front of the perforation. Tubing is then pulled back above the cement and squeeze pressure is applied to force the cement into its desired location. Tubing is being cleared from cement by reverse circulation. Figure 33 depicts three steps involved in Bradenhead squeeze technique.

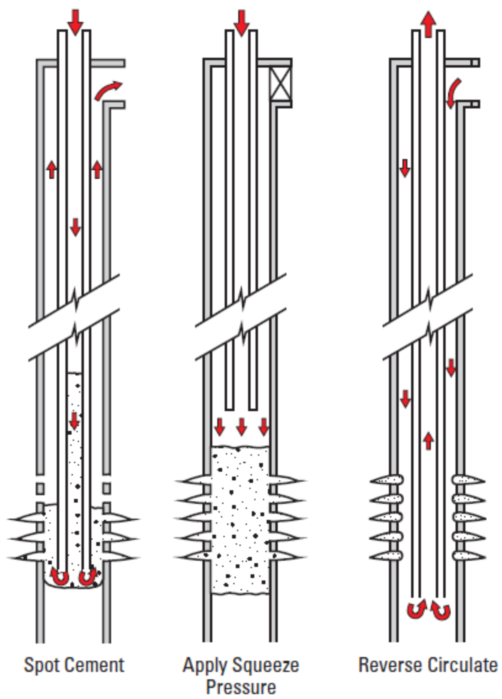


Figure 33: Bradenhead Squeeze Method [2]

Squeeze tool technique employs the use of mechanical tools in order to isolate casing and other surface equipments from high squeeze pressure. The tools can be of the type of retrievable squeeze packer or drillable cement retainer. Packer type tools can be set at the desired depth to isolate everything above it and can be released several times. Figure 34 shows schematic of bridge plug and squeeze packer. Cement retainer is an isolation tool which is made a part of casing so that the annulus above it can be protected from the pressure loads of squeeze cementing job (figure 35).

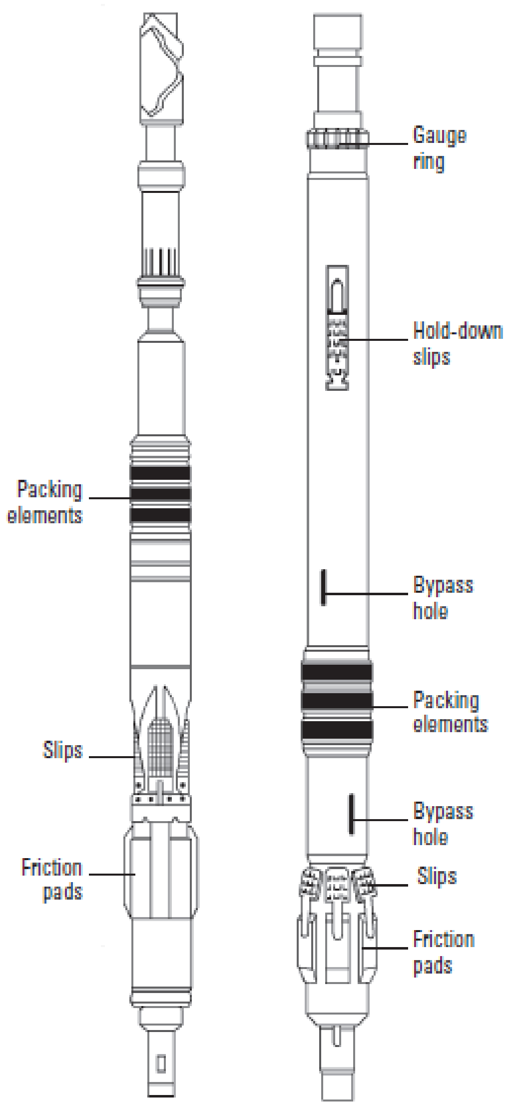


Figure 34: Bridge Plug and Squeeze Packer [2]

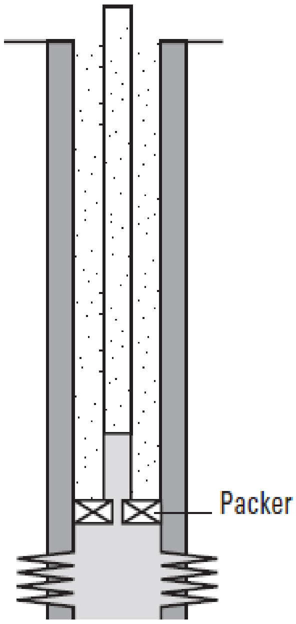


Figure 35: Squeeze with Cement Retainer [2]

1.7 Evaluation of Cement Job

The cement job evaluation is done to determine the success of cement job in achieving its objective. The objective of casing cement job varies with the type of casing. For conductor, cementprevent the hole erosion from drilling fluid. Surface casing cement must protect water bearing formation and must aid casing in supporting deeper casing strings. Intermediate casing are cemented to isolate abnormal pressure formation and problematic zones from rest of the well bore. Cementing of production casing has its goal to maintain zone isolation and protect hydrocarbon from migrating or leaking into annulus. Perforation sealing, repairing casing leaks, improving quality of primary cement job are the major objectives of remedial cementing jobs. There are several techniques that are being used to evaluate cement job.

- Hydraulic Testing methods (pressure testing and inflow testing)
- Non-destructive techniques (nuclear, noise and temperature logging)
- Techniques based on acoustics (sonic, acoustic and ultrasonic logging)

2 POTENTIAL IMPROVEMENT AREAS IN CEMENTING OPERATIONS

2.1 Wait On Cement (WOC)

After the cement slurry has been placed in the well, it starts to harden and develop compressive strength. WOC is the time which starts from mixing till compressive strength gets developed after bumping the plug. The compressive strength is generally taken as 500 psi and the time required to reach this value depends upon different factors such as water to cement ratio, temperature along the well, composition of cement, additives etc.

Many researchers have investigated different cements by analyzing the strength development in order to minimize wait on cement. Maier discussed the dependence of wait on cement on curing temperature and water to cement ratio (WCR). He stated that the higher the curing temperature the less the WOC. This temperature depends upon heat of hydration, mud temperature and formation temperature for surface casing, it also depends on time of the year considering winter or summer. He focused on Class A, B and C and proposed various advantages of densified cement slurries. He also studied the effect of heat on hydration of cement under different conditions and came to the conclusion that WOC can be minimized by maximizing the heat of hydration which then can be increased by pumping slurry at higher temperature, increasing the amount of slurry and using highly dense slurry [9].

In order to determine the WOC time, an indirect analysis on compressive strength development was done by studying the tensile strength of 10ft cement sufficient enough to hold the casing in place. It was found out by previous works that 10ft of cement, having 8psi tensile strength, would hold 200ft of casing in lighter weights of the common size used in the field, however for surface casing, one should consider the heavy drillbits attached to drillpipe too. To determine tensile strength of the cement, the following relationship is used: [9].

$$\mathrm{Ts} = \frac{\mathrm{LW}}{9.69\mathrm{dh}} \qquad (4)$$

Where,

Ts	=	Tensile Strength
L	=	Length of the casing
W	=	Weight of the casing
d	=	OD casing
h	=	Height of cement column

Table 3 shows the result of the analysis.

Table 3 Length supported by 10 feet column of 8 psi tensile strength cement [9]

CASING		DRILL COLLAR		LENGTH SUPPORTED BY CEMENT (FT.)
Size (in.)	Weight (lb/ft.)	OD (in.)	ID (in.)	
7	17.00	4-3/4	2	94
8-5/8	24.00	6-1/4	2-1/4	67
10-3/4	32.75	6-3/4	2-7/8	72
13-3/8	48.00	9	3-1/4	50

As seen from table 3, 8 psi tensile strength is holding sufficient length of casing. As a general rule, compressive strength corresponding to 8 psi tensile strength is considered 100psi approximately. Since the time difference between this strength and initial setting time for cement is very small, a safety factor was suggested and a new minimum compressive strength 500 psi was taken as a standard practice. This may be too high, but this is suggested to avoid the possibility that the cement may not be set at all which could lead to collapse. Minimum strength of 250 psi was proposed to drill further [9].

However, in places where there are no regulations about WOC time, there are many cases where they only wait 3-4 hours before drilling next section, this applies for summer time and during winter they use 6-8 hours, without compromising the safety of the well.

Maier further discussed about WOC as function of temperature to achieve 500psi and 250psi for different cement slurries. He designed slurries with different concentration having different WCR (Water Cement Ratio) [9].

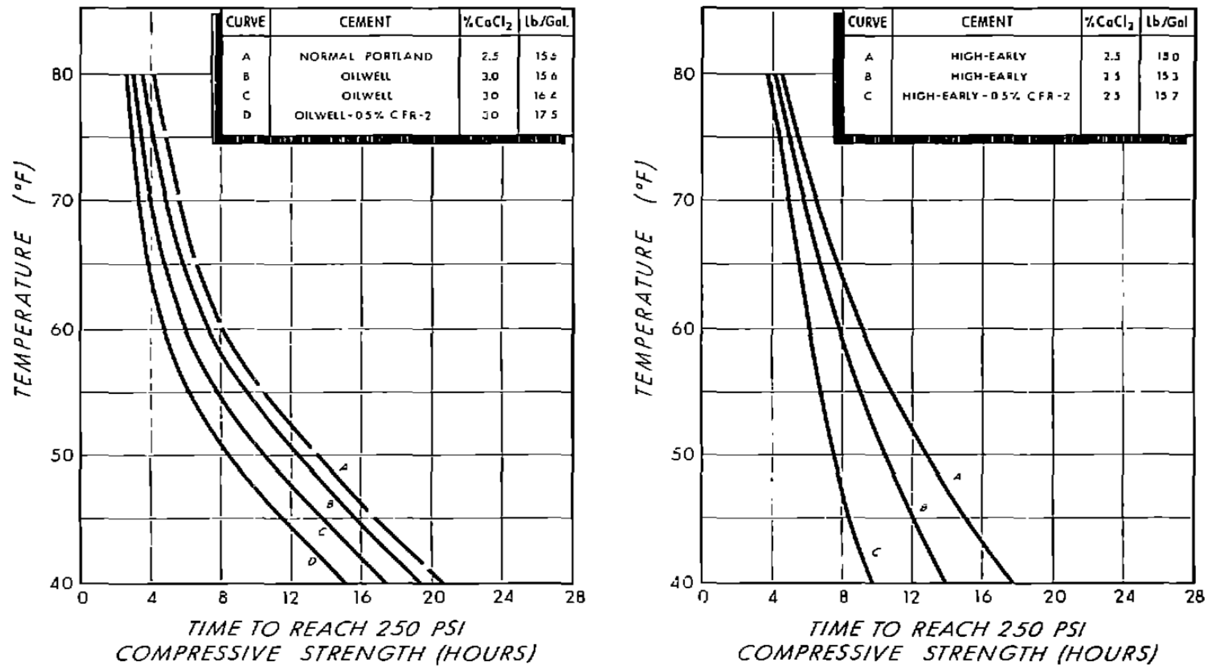


Figure 36 Compressive Strength Development of Cements up to 250 psi for different cement types with different densities [9]

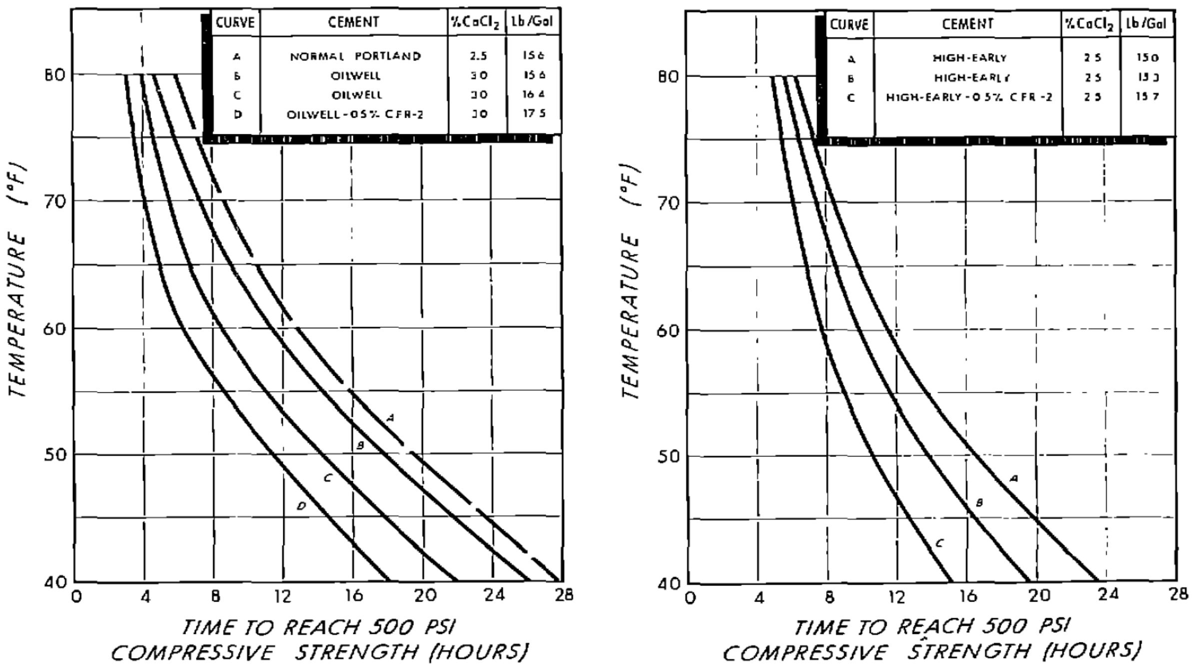


Figure 37 Compressive Strength Development of Cements up to 500 psi for different cement types with different densities [9]

The effect of curing temperature was also taken into consideration by studying the temperature profile in 11 wells after placing the cement. Due to evolution of heat of hydration from cement and heat transfer from formation, the temperature at a particular depth showed an increasing trend which actually results in lowering the WOC [9].

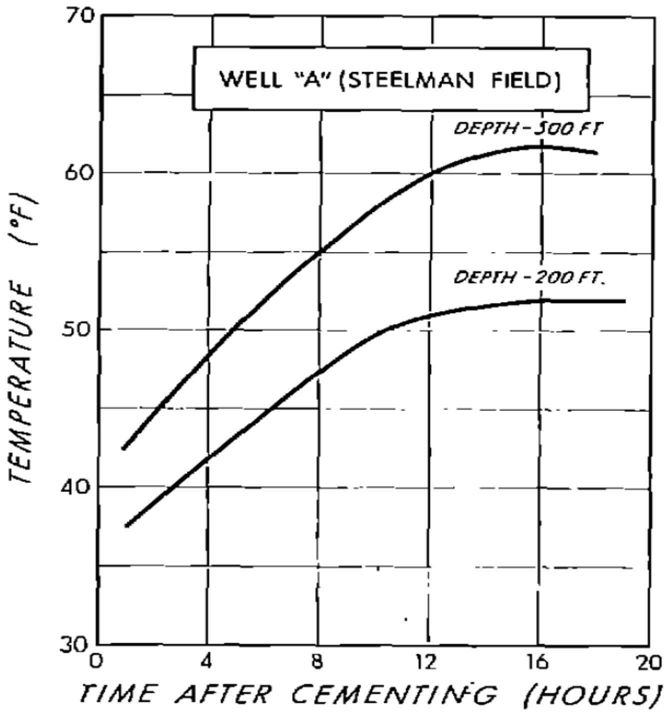


Figure 38 Development of Temperature during cement hydration [9]

The effect of density on WOC was also analyzed at different temperatures and it was found out that highly dense slurries have less WOC [9].

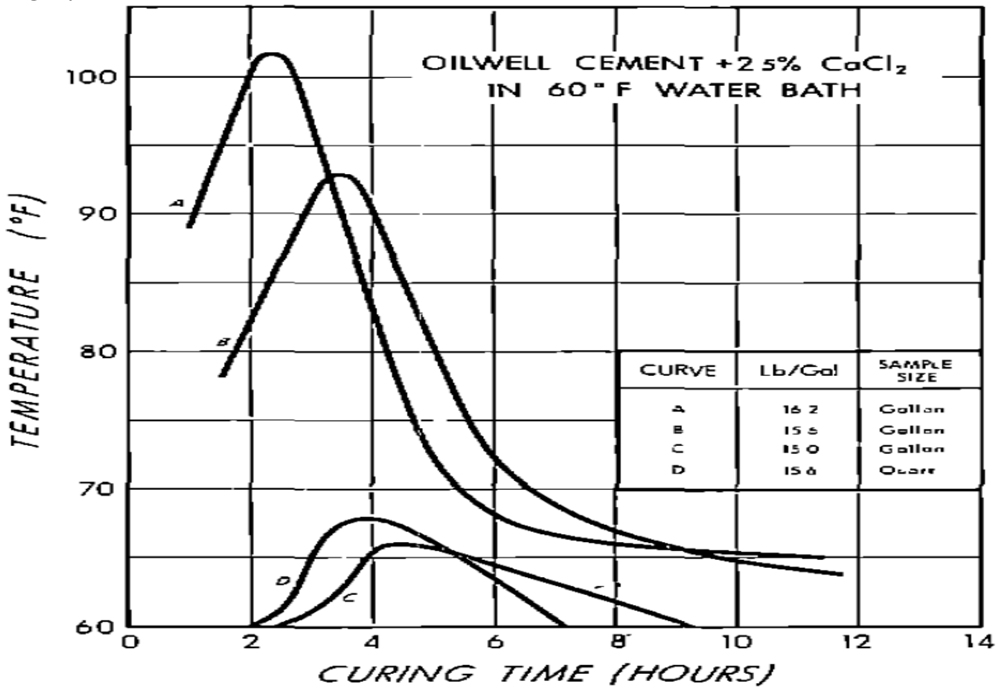


Figure 39 Temperature Profile with Curing Time [9]

The support coefficient relationship with tensile strength is obtained from briquette mold for different types of cements. A test specimen (Figure 40) was used to analyze the cement supporting capacity. A briquette mold (Figure 41) was used to determine the tensile strength of cement. [10]

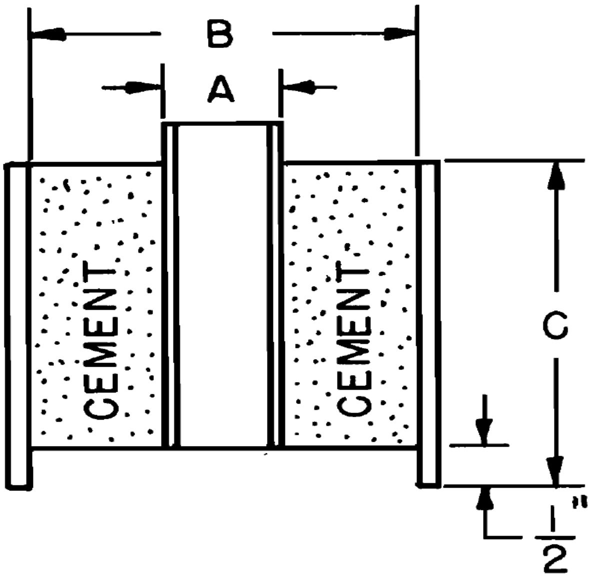


Figure 40 Specimen used for Determination of Cement Support Coefficient [10]

Figure 41 Briquette Mold used to measure tensile strength of cement [11]

The results from both tests are shown in Figure 42.

Test No.	API Class of Cement	Tensile Strength, Psi	Casing Size: Outside Diameter of Inside Pipe, In (A)*	Casing Size: Inside Diameter of Outside Pipe, In (B)*	Casing Size: Length, In (C)*	Force to Break the Cement Bond, Lb	Support Coefficient, Psi
1	A	18	1 301	2 05	4	196	13 7
			2.375	3 50	4	381	14 6
			5.5	8.00	4	907	15.0
2	A	33	1 301	2 05	4	580	40 5
			2.375	3 50	4	1,160	44 4
			5 5	8.00	4	2,805	46.4
3	A	75	1.301	2 05	4	1,320	92.3
			2.375	3.50	4	2,920	112
			5.5	8 00	4	6,225	103
4	C	7	2.375	4 89	4	131	5.0
			2.375	4.89	8	199	3.6
			2.375	4 89	16	843	7.3
5	C	28	2 375	4.89	4	640	24 5
			2.375	4 89	8	1,690	30 2
			2.375	4 89	16	3,810	32.9
6	C	71	2.375	4 89	4	3,800	146
			2.375	4 89	8	5,860	105
			2.375	4.89	16	12,925	112

Figure 42: Influence of Diameter and Length of the Casing on Support Coefficient [10]

The support coefficient depends upon force required to break the cement bond when it is placed in 10ft length outside the casing in the annulus. It can be seen that the support coefficient increases with the increase in tensile strength value [10].

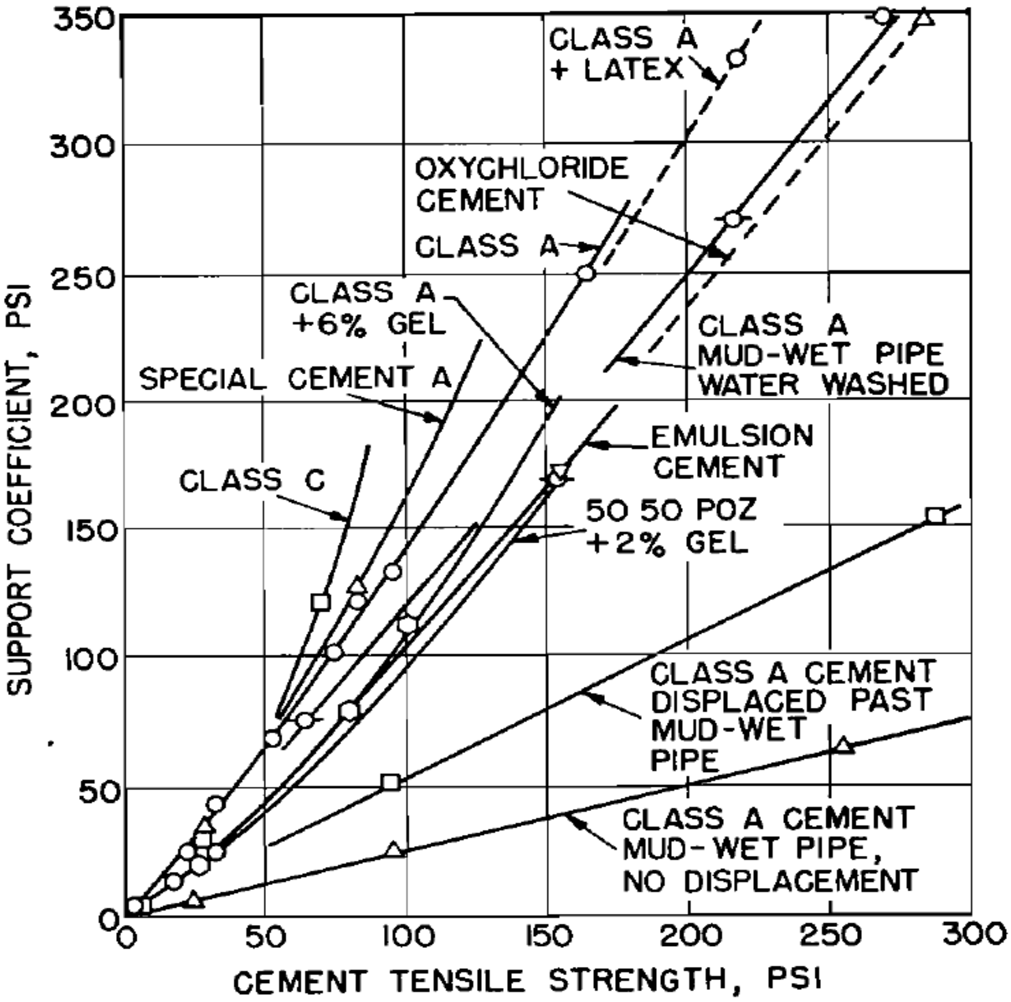


Figure 43 Support Coefficient increases proportionally with Cement Tensile Strength [10]

Similar conclusion about value of minimum tensile strength was obtained from this experiment and it suggested that, if precautions were taken, as low strength of cement as 8 psi tensile strength (100 psi compressive strength) can support casing before further drilling thus reducing WOC time. However, to set in mind the initial setting time for cement, one should wait more. For most operations in surface casing, 250 psi compressive strength is sufficient to drill out, the good news is that time required to develop 250 psi is only 25-50% longer than what is required to develop 100 psi. In order to quantify WOC, several experiments were performed with different slurries to find WOC at different curing temperatures. It was found that the observed WOC was lower than the standard WOC recommended by API, and since the observed WOC was found to be lower, it was needed to compare it with the thickening time since the cement should be able to be pumped before it sets. Thickening time for surface casing was analyzed statistically for a number of casings at different setting depths and different temperatures and it was concluded that time to develop 8 psi tensile strength is compatible with the thickening time as shown in figure 44 [10].

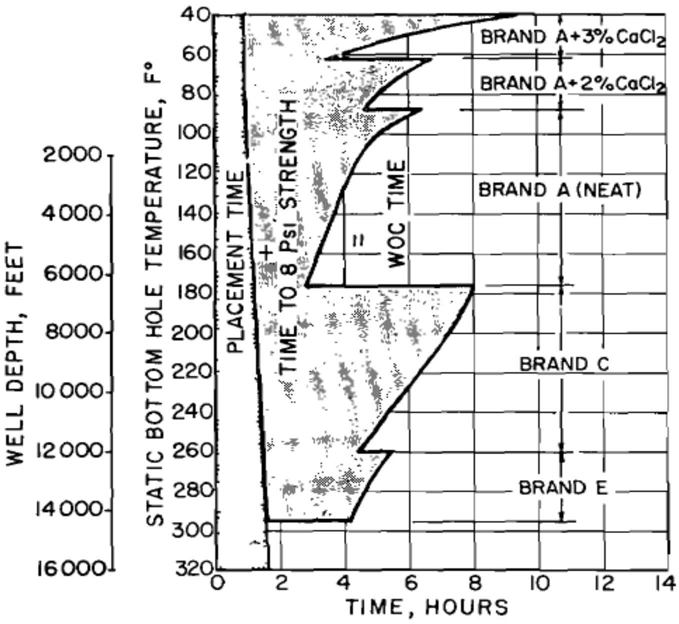


Figure 44 conclusion of the statistic which includes the placement time too and shows how the 8 psi tensile strength time is compatible with the minimum thickening time. [10]

2.2 Conditioning Hole and Mud

2.2.1 Introduction

A poorly drilled hole may have problems such as large dogleg sections. Washouts,thick filter cakes, or settled solids beds could be the results of poorly treated mud. The hole may also haveseveral washed-out zones that are difficult to clean out,regardless of the displacement rate. Furthermore, thesewashed-out pockets have a tendency to trap gelled or dehydratedmud that may be dragged out by the cement slurry, contaminating the cement column above it [2].

2.2.2 Borehole quality

Efficiency of cementing operation can be affected badly if the bore hole has following characteristics:

- Uncontrolled subsurface pressures
- Rough Wall
- High Dogleg Severity
- Under-gauge/over gauge
- Unstable
- Improperly cleaned
- Untreated and immobile mud

This situation can be achieved easily if care is not taken. Therefore, a lot of concern should be taken during cementing to reduce the effects of poor well preparation [2].

2.2.3 Mud conditioning

Drilling muds are designed to facilitate drilling operationsand provide proper cuttings transport. They are notnecessarily conducive to efficient mud displacement,logging, or completion operations. Therefore, it is oftennecessary to condition themud (i.e., to modify its properties).Before placing cement in the wellbore, two mudcharacteristics can be changed—density and rheology. The required adjustments vary according to the particularsituation. It is generally desirable to reduce the mud density without compromising well control. Reducing the mud gel strength, yield stress, and plastic viscosityis also beneficial. Doing so reduces the driving forces necessaryto displace the mud and increases mud mobility. Ofcourse, these steps require prior removal of the cuttingsfrom the borehole and the drilling fluid [2].

2.2.4 Evaluating well bore condition

Normally wiper trips are performed in order to check hole condition. Wiper trip is an abbreviated recovery and replacement of the drillstring in the wellbore that usually includes the bit and bottomhole assembly passing by all of the openhole, or at least alloftheopenholethatisthought to be potentially troublesome. This trip varies from the short trip or the round trip only in its function and length. Wiper trips are commonly used when a particular zone is problematic or if hole-cleaning efficiency is questionable.

If tight hole or bridging conditions happen during trips, thepipe is pulled back to the nearest stand and reaming/washing commenced in accordance with stuck pipe procedure. If tight spots occur while tripping out, the top drive orKellyisusedto commencereaming and circulating out.

During the trip, care use to be taken to minimize surge/swab pressures by controlling the speed of pipe movements. During hole swabbing, thepipeis run back to bottom and the hole is circulated bottoms up. Mud loggers run the swab program prior to each round trip to determine the maximum trip speed.

Before pulling out of the hole, the trip tank is normally filled. The drilling contractor usually ensures that a master drill pipe tally book is maintained at all times. It includes stand number, single number, single identification, drill pipe grade, single length, stand length and total length. While tripping it is always recommended to perform flow checks especially at just off bottom, at the casing shoe, prior to pulling drill collars through BOPstacketc. [12].

2.2.5 Conditioning mud prior to complete POOH

Before thepulling out of hole to run the casing, theholeiscleaned until there are no further cuttings returns at the shakers.It is normally witnessed by the Mud Engineer and Mud Logger. To improve displacement efficiency, the mud is conditioned to reduce the rheology during circulation. Solids control equipments are run to remove drill solids from the mud thus reducing PV to the lowest practical level. Dispersants / thinners are added to reduce the yield point(YP) and 10 minute gel strength. (YP not reduced in high angle wells). The mud must be completely free of gas after circulating. Circulationis continued until a full annular volume has been pumped with no indication of gas.

2.2.6 Conditioning mudafter running casing

The mud should be circulated after the casing is inplace, because the well may have been static for a longperiod, allowing the mud to gel or build a filtercake. Theminimum circulation volume should be at least “bottomsup” and preferably greater. Unfortunately, at this stage, operators commonly perform only mud conditioning. If cuttings, or gelled or dehydrated mud, are scraped into the mud while running the casing, an excessive pressure buildup can occur when circulation is resumed. Therefore, it is often desirable to circulate the annulus at intermediate depths before the casing reaches the bottom of the hole.

2.3 Pumping Procedures and Displacement Rate

2.3.1 Pumping Procedure

Proper primary cementing is imperative in order to save time by avoiding remedial cementing. There are basically two cementing procedures. Batch cementing is one of the cementing method in which the cement is premixed in the “batch tank” before pumping it in the well. This isto ensure delivering homogenous slurry during the hole cementing job. Batch cementing is usually used for smaller operations as the capacity of the “batch tank” is limited, normally about 50-100 barrels.

Until 10-15 years ago batch mixed cementing had to be placed immediately after mixing as the hydration process began right after the mixing. But research and development in the technology made it possible to keep the mixed cement in liquid state for longer periods of time allowing performance test and strength test of the cement to be conducted before pumping it down.

The other cementing procedure is called “on-the-fly” cementing. This is a continuous method without premix, which can be manualorfullyautomatic. With this method cement can be mixed more easily on the rig, without needing the “batch tank”, and slurry properties can be adjusted along the cementing procedure considering different well conditions like temperature changes and pressure changes. Since this procedure can be automated, other benefits of it would be reducing personnel and time on the rig. “On-the-fly” cementing is usually performed for larger cement jobs such as intermediate casing and production casing cementing, usually cement jobs with more than 200 barrels. The goal of achieving homogenous slurry throughout the cement job is not possible with this method, and here is where the batch cementing is preferred in certain cementing jobs [13].

2.3.2 Significance of displacement rate with respect to pumping time

In order to study the significance of displacement rate, a simple well (Figure 45) is constructed in commercial software and casing cementing job is being analyzed by varying the pumping rate of cement slurry, spacers and displacement mud. The position of different fluids after jobis shown in Figure 46.

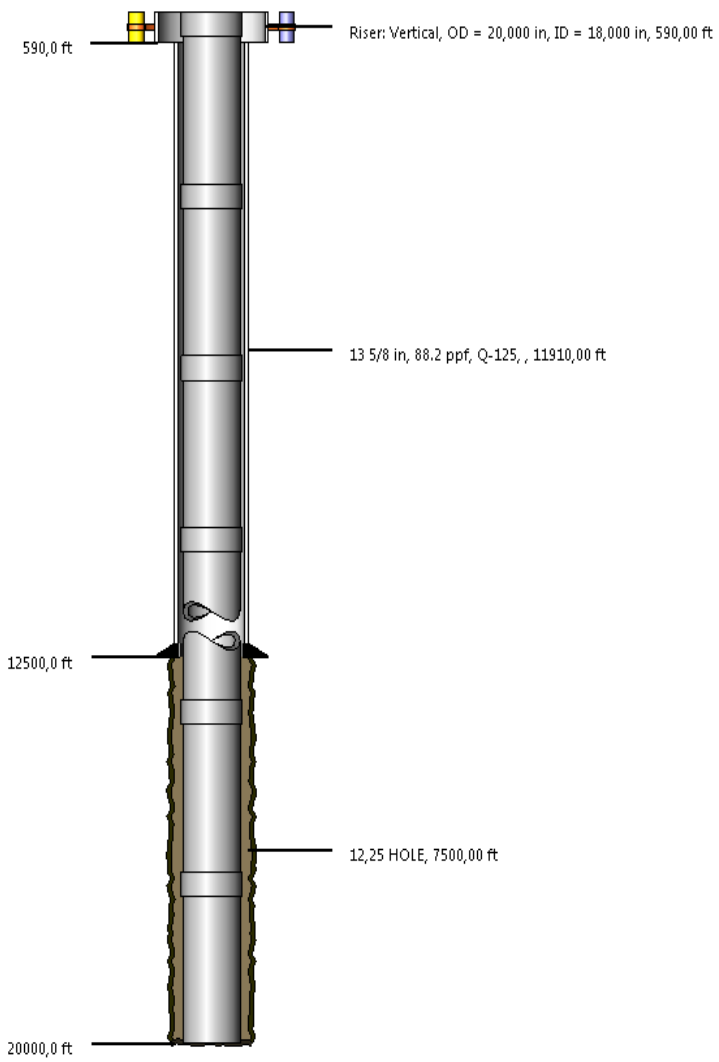


Figure 45 Well Construction

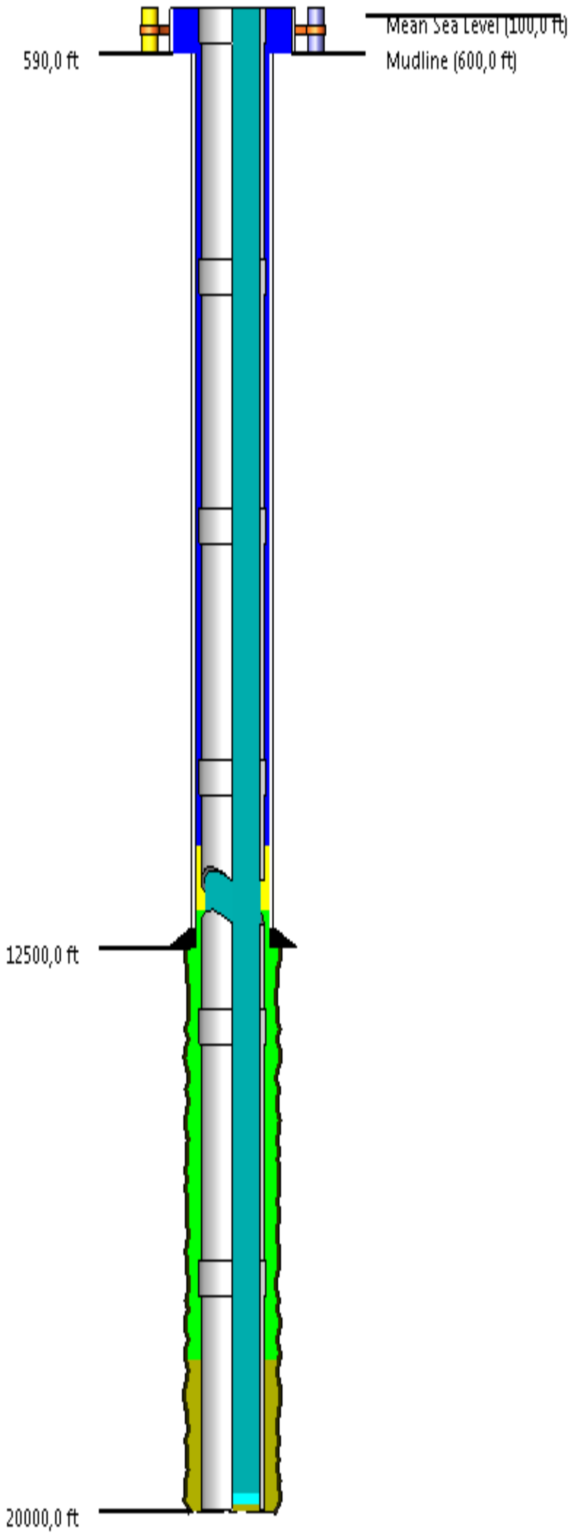


Figure 46 Position of Fluids after Cement Job

Different pump rates are selected based on the available capacity of cementing pumps and industry practice. The goal of the study is to highlight how a large amount of time can be saved during cementing if pumping rates are selected efficiently. It will also reduce the quantity of retarders in the cement composition which are being added to ensure that the cement should not set during pumping. Care should be taken while selecting a higher pump rate as it can lead to fracturing the wellbore. Table 4 shows the result of simulations being run on different pumping rate.

Table 4 Effect of Pumping Rate on Total Cement Job Time

S.NO	PUMPING RATE (BPM)	TOTAL TIME (MINUTES)	SURFACE PRESSURE (PSI)	WELLBORE CONDITION
1.	2	961.71	1301.26	Safe
2.	4	483.36	1381.1	Safe
3.	6	323.91	1461.48	Safe
4.	8	244.19	1542.41	Safe
5.	10	196.35	1623.89	Safe

The simulation is also run to analyze whether the maximum equivalent circulation density (ECD) and minimum hydrostatic gradient lie between pore pressure and fracture pressure. The results of these simulations are shown in Figures 47, 48, 49, 50 and 51.

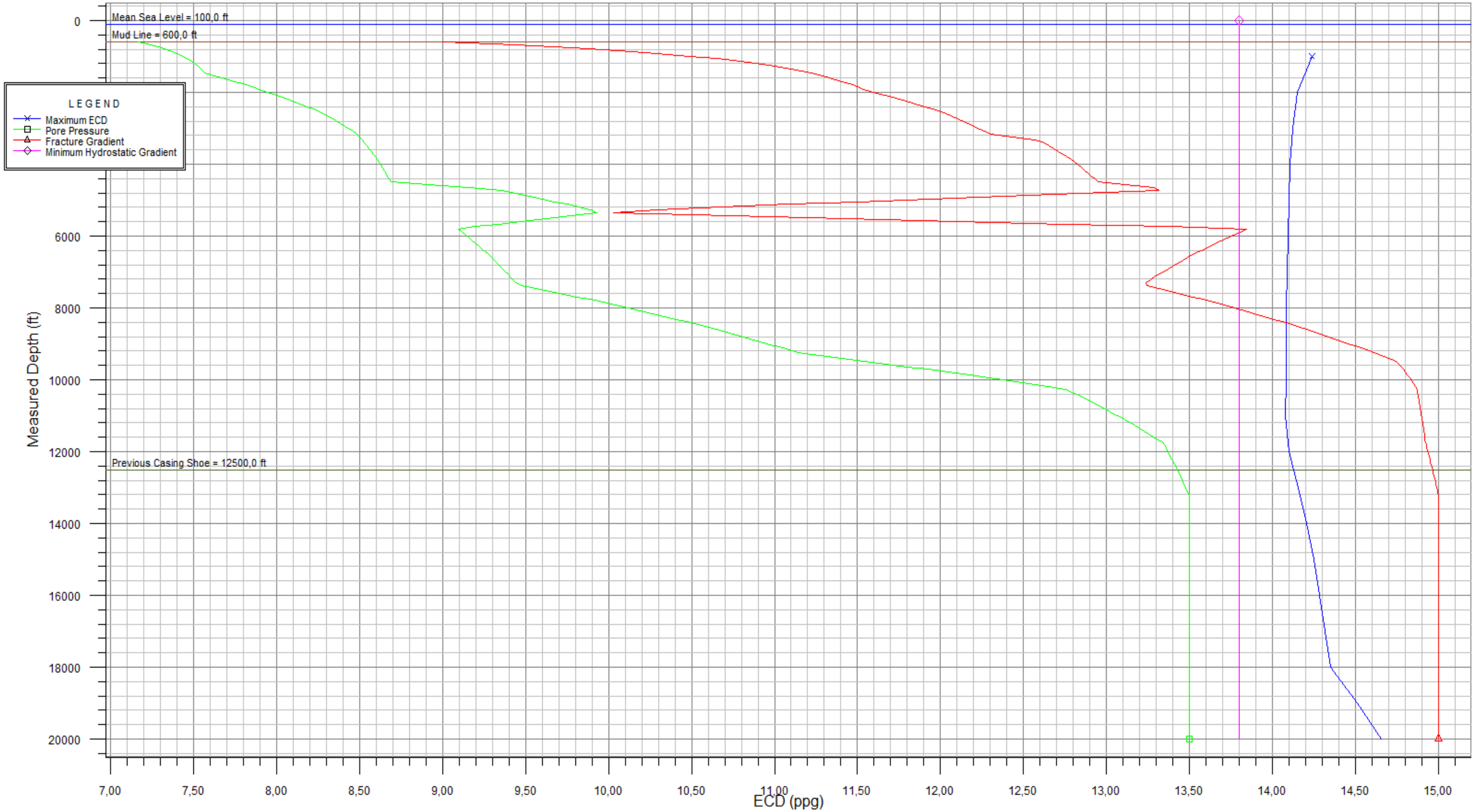


Figure 47 Maximum ECD and Minimum Hydrostatic Gradient at 2BPM

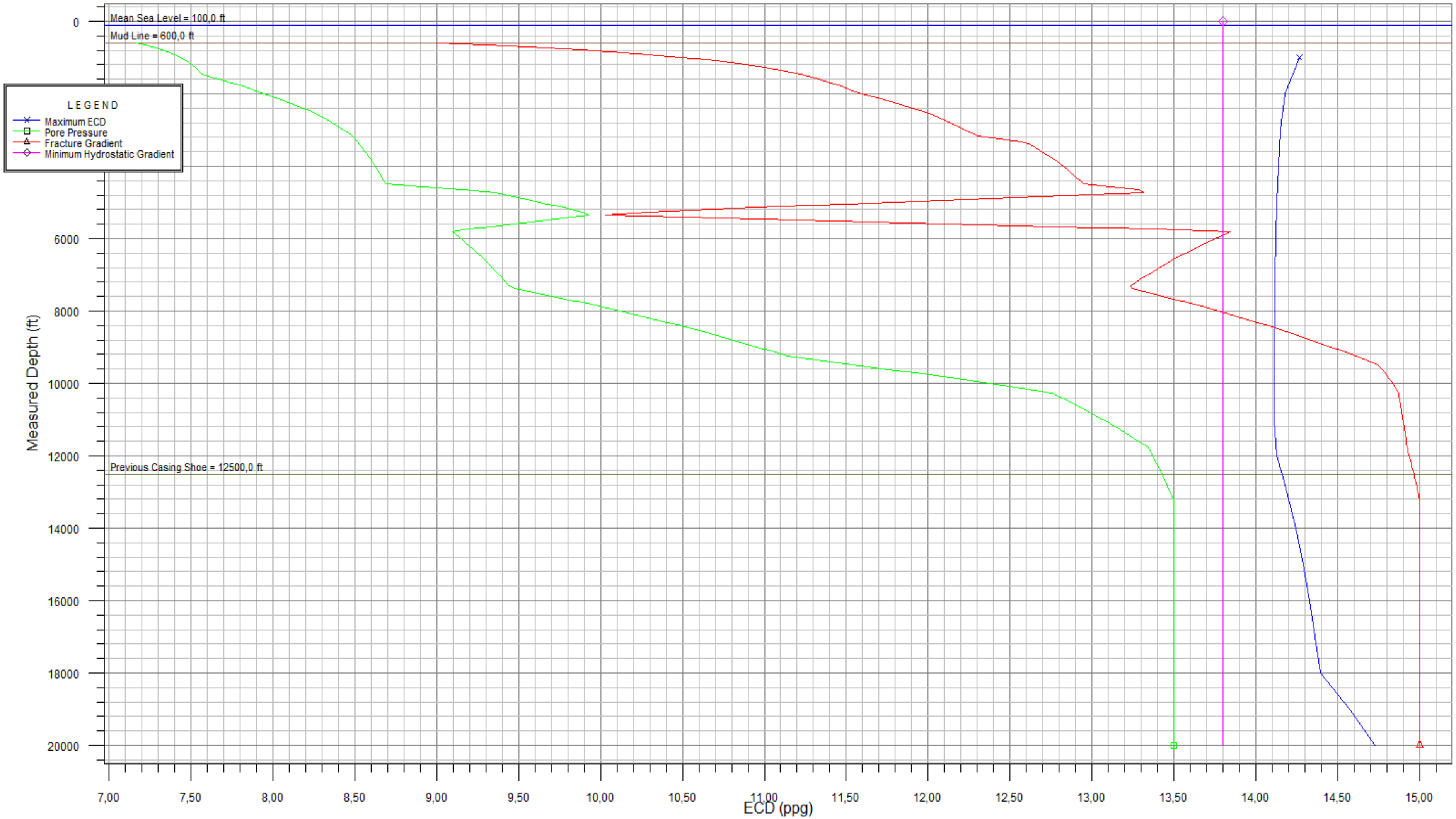


Figure 48 Maximum ECD and Minimum Hydrostatic Gradient at 4BPM

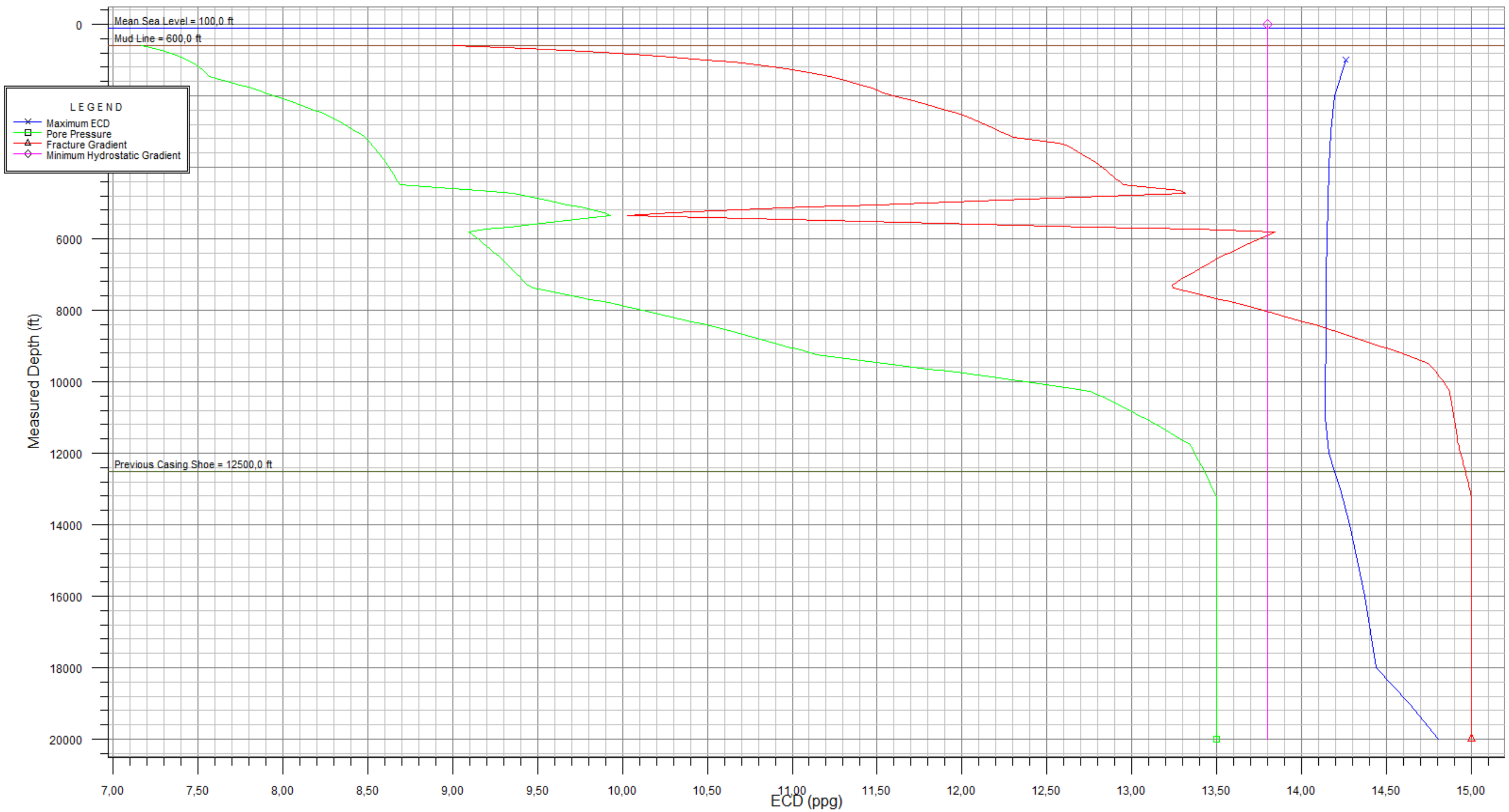


Figure 49 Maximum ECD and Minimum Hydrostatic Gradient at 6BPM

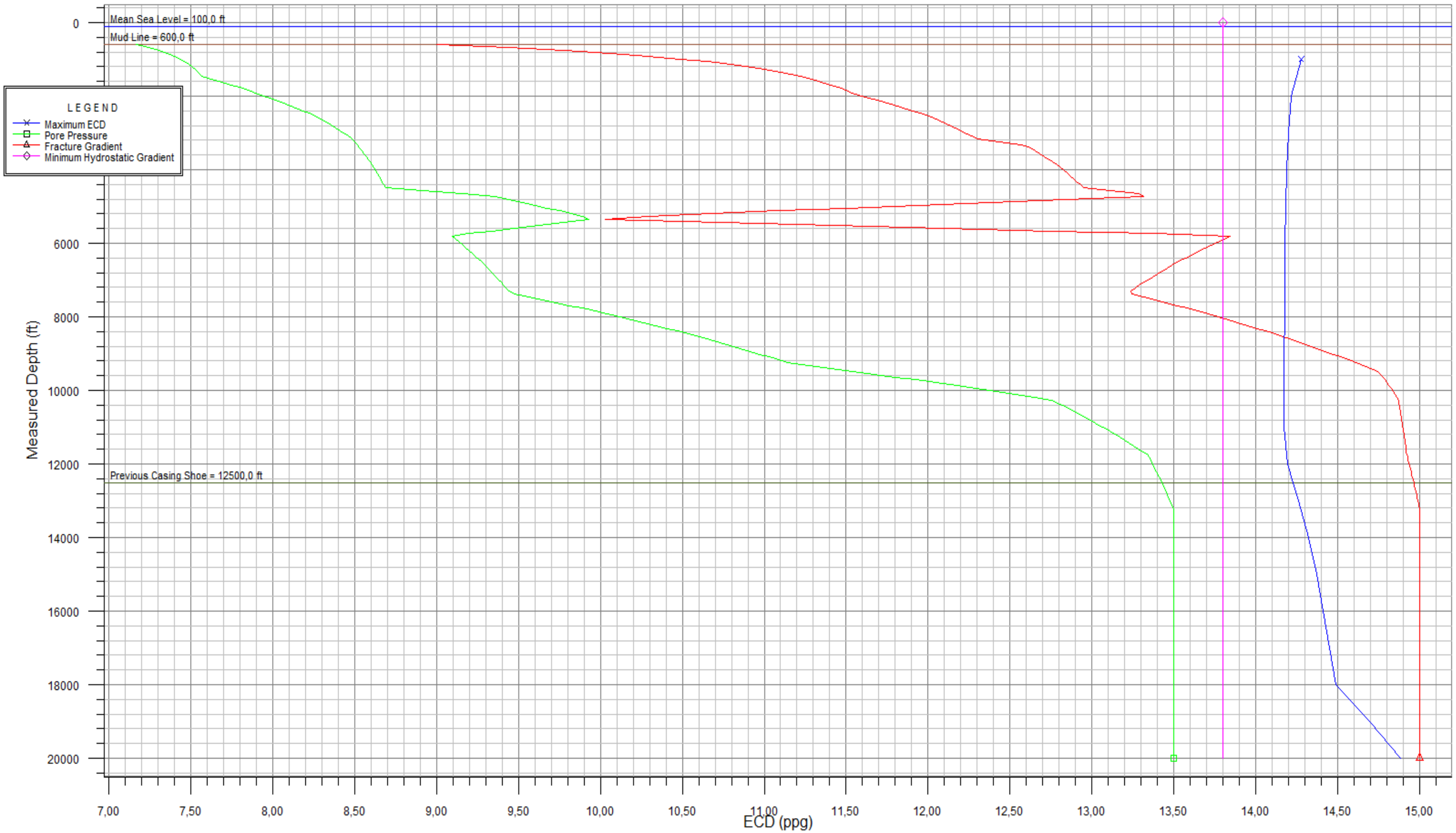


Figure 50 Maximum ECD and Minimum Hydrostatic Gradient at 8BPM

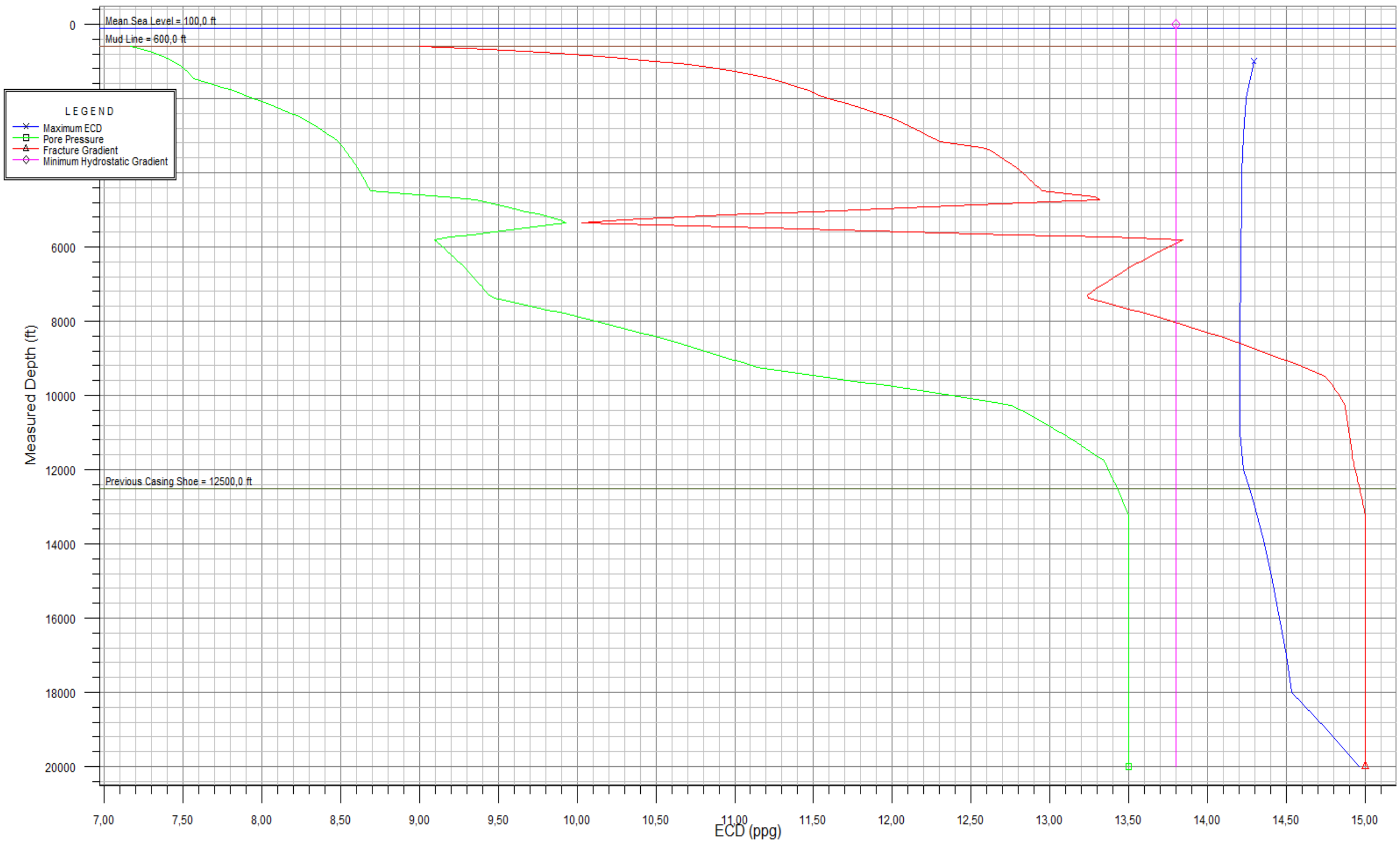


Figure 51 Maximum ECD and Minimum Hydrostatic Gradient at 10BPM

The Figure 52 shows the plot between pumping rate and total time during cementing.It is obvious from the figure that the selection of pumping rate can lead to the saving of couple of hours. But some other factors should be kept in mind while selecting the maximum possible pumping rate such as formation fracture pressures, cement channeling, burst resistance, collapse resistance etc.

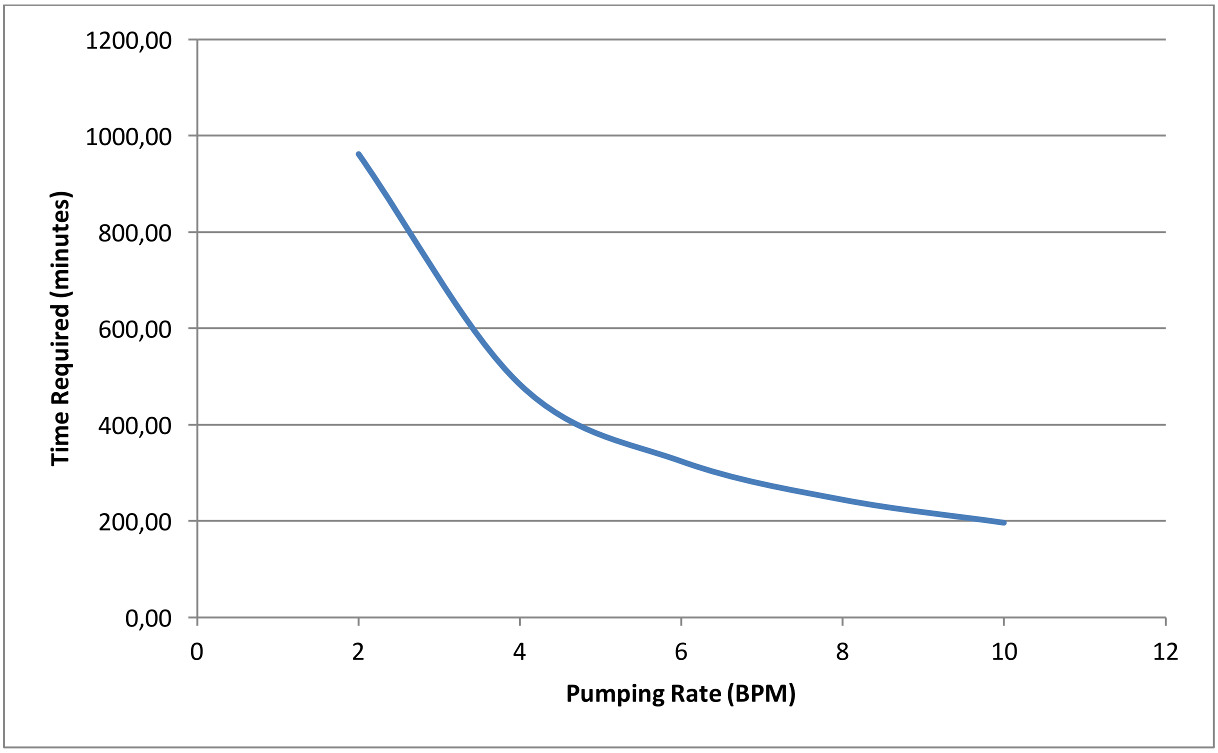


Figure 52 Summary of Results

2.4 Casing Centralization and Cement Channeling

2.4.1 Centralizer

2.4.1.1 Introduction

Centralizer is a mechanical device used to ensure that the casing have no contact with wellbore walls by securing it around the casing. This results in a continuous annular clearance which is necessary for a good cement job. Mud channeling avoidance, proper zonal isolation, ease in casing running and minimized risk of differential sticking are among the several benefits of using centralizeraround the casing. Since the use of centralizer is very critical with respect to cement job quality, both operators and service companies are always interested to find the right type and correct place of centralizer.

2.4.1.2 Types of Centralizers

There are 4 types of centralizers; bow-spring, rigid, semi-rigid, and mold-on

A. Bow-Spring

These types of centralizers are slightly larger than the wellbore. They are suitable for both vertical and slightly deviated wells. It has a tendency to pass through tight spots. Restoring force of bow centralizer is an important factor because it determines its effectiveness. Due to limited restoring force, the side force created by casing when running in highly deviated wells is way beyond its working limit. Therefore, solidcentralizer is used for those kinds of applications.

Figure 53 Bow Centralizer [14]

B. Rigid

Rigid centralizers are made of solid steel bar having a particular blade height. They are used in deviated wellbores irrespective of the sideforce. Due to fixed height of the blade, they only fit in a specific casing or hole but the advantage of using this type of centralizer is guaranteed standoff and ease in pipe rotation.

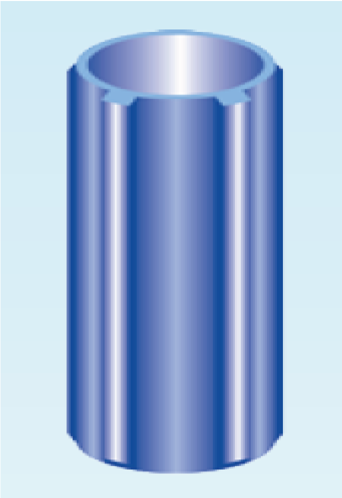


Figure 54 Rigid Centralizer [14]

C. Semi-Rigid

It is kind of hybrid centralizer between bow and rigid type. It has double-crested bows which give it a spring feature so that it can easily pass through the tight spots. It also provide large enough restoring force which is only associated with rigid type of centralizer.

Figure 55 Semi Rigid Centralizer [14]

D. Mold-On

It is made up of carbon fiber ceramic materials which are directly applied to the exterior surface of casing. Use of carbon fiber (non-metallic surface coatings) is used to reduce the friction especially in extended reach wells. The important design features of mold-on centralizers are blade length, angle and spacing.

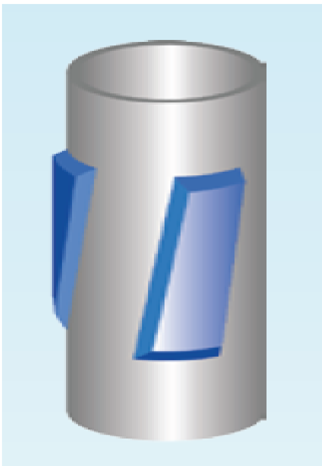


Figure 56 Mold-on Centralizer [14]

2.4.1.3 Standoff

It defines the extent to which the casing is centered. A perfectly centered casing has a standoff of 100% whereas casing touching the wellbore wall has standoff equal to 0%. It is recommended that the standoff value for a any casing running job should be above 67% regardless of centralizer type to ensure good cement job.

$$Standoff = \frac{C}{A-B} \qquad (5)$$

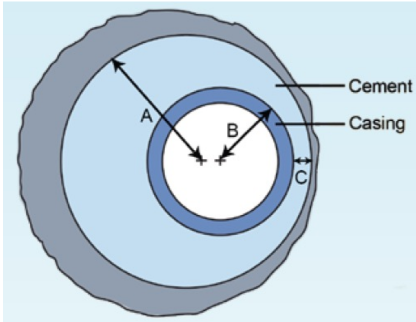


Figure 57 Areal view of Wellbore with Casing and Cement [14]

Inorder to find optimimal number of centralizers and its placement, adoption of an engineering analysis can help both operators and service companies.

The casing standoff is a function of following conditions:
- Well path and hole size
- Casing OD and weight
- Centralizer properties
- Location and densities of mud and cement slurries (buoyancy)

2.4.2 Centralizer Selection and Placement:

Nowadays, several computer models are available to design the centralizer placement by optimizing standoff as well as number of centralizers required to achieve the standoff. A study is done using Landmark's EDM suite WellPlan for centralizer selection on a horizontal well (Figure 58). The vertical section and plan view are shown in Figure 59 and Figure 60 respectively. The aim of the study is to place minimum number of centralizers to save cost and time without comprising the desired standoff requirement which is set at 70% in the study.

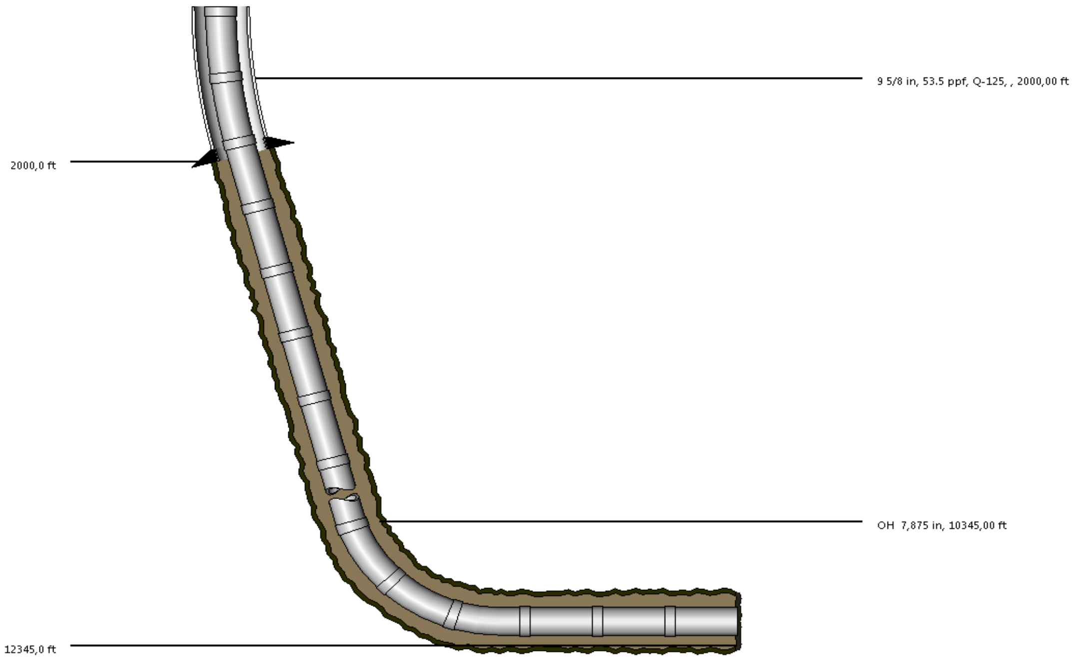


Figure 58 Well Construction

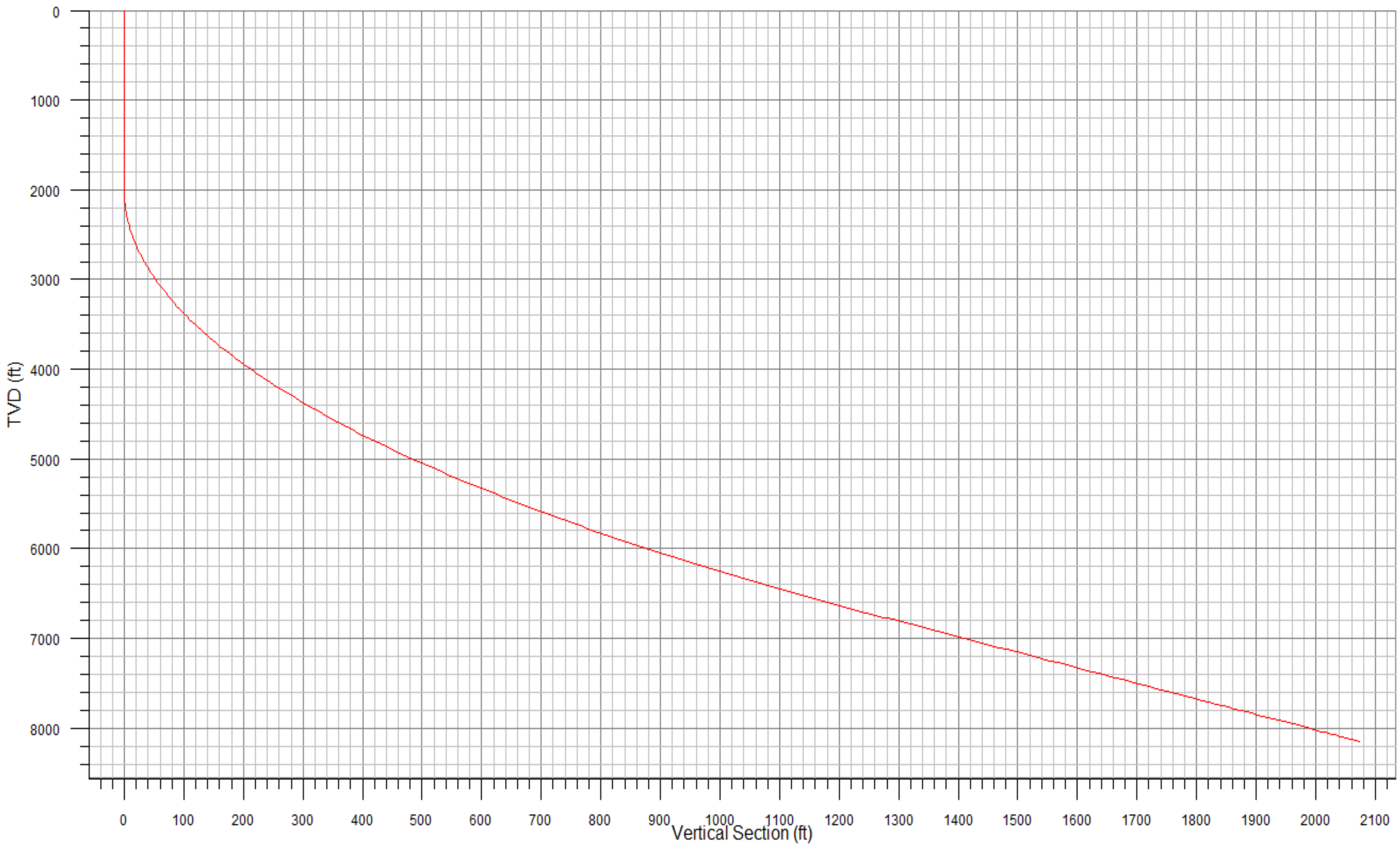


Figure 59 Vertical Section

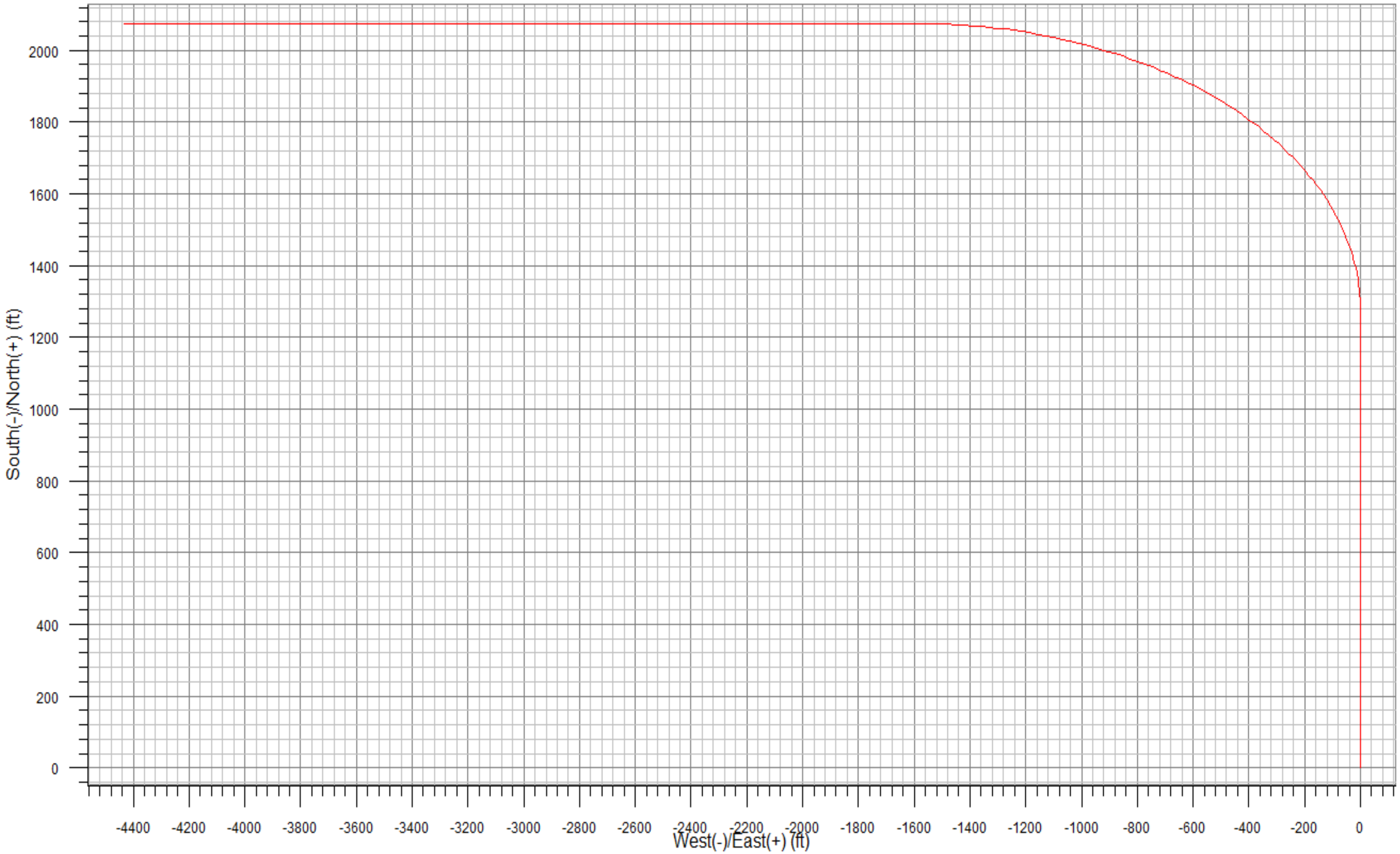


Figure 60 Plan View

Following three modes are analyzed on the designed well by using bow centralizer.

- Specify Spacing
- Specify standoff
- Optimum spacing

2.4.2.1 Specify Spacing

In this approach, the effect of spacing variation is studied and different standoff profile is observed keeping in mind that the minimum standoff should be higher than 70%. This mode allows simple to install centralizer placement due to its fixed spacing. Table 5 shows the summary of this calculation mode.

Table 5 Results with Specify Spacing Mode of Calculation

MAXIMUM SPACING (FT)	MINIMUM SPACING (FT)	CALCULATED NUMBER OF CENTRALIZER
20	20	618
30	30	412
40	40	100

Figure 61 and Figure 62 show that the standoff is very good along the whole casing. But this placement may be too conservative as too much centralizer has to be used in these scenarios.

Figure 63 depicts the standoff results for 40ft spacing (1centralizer per joint). It is clear from the figure that the standoffis acceptable in less deviated sections (upto 7000m) but then it shifts toward a value less than 70% in highly deviated section. This will increase the risk of potential cementing problems.

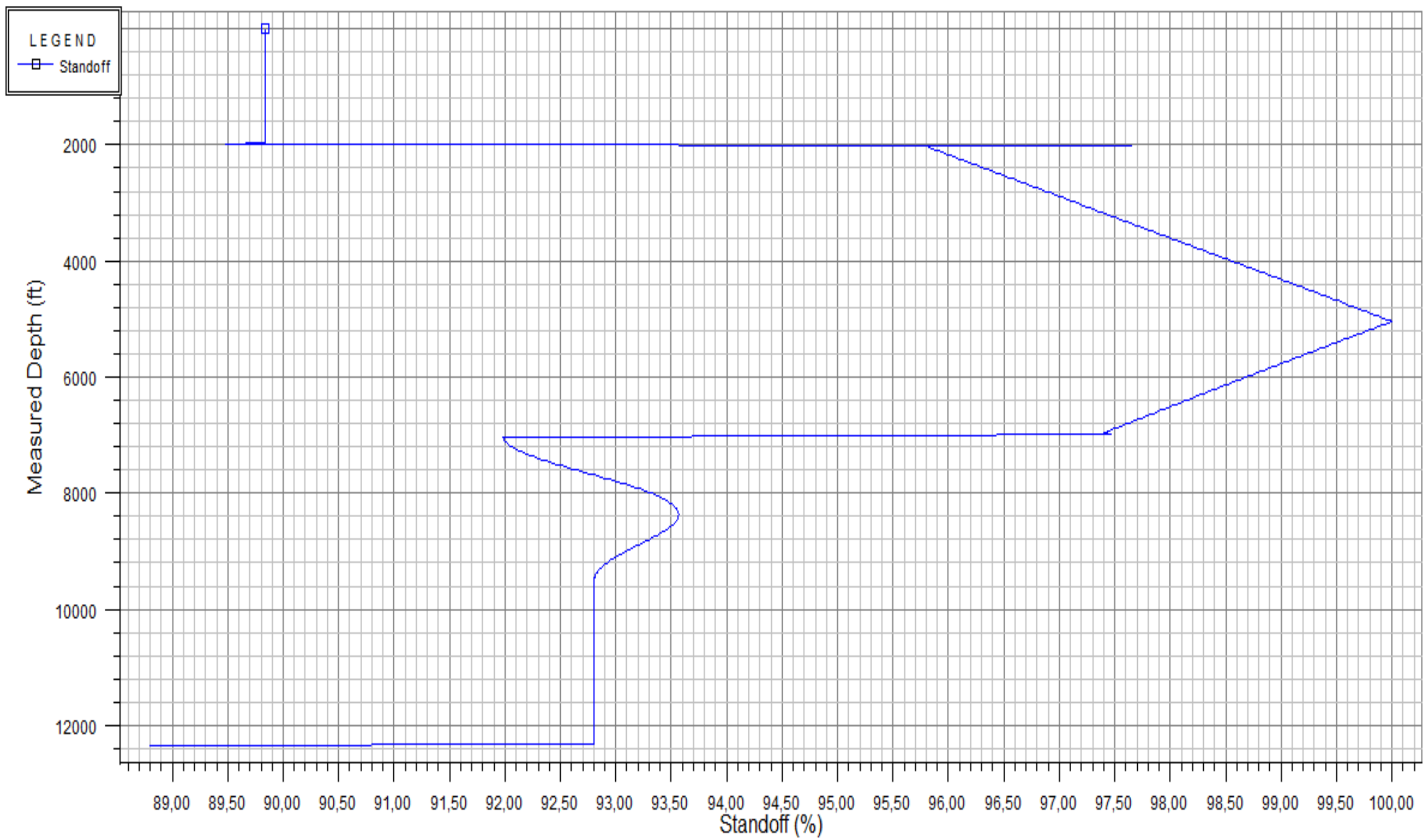


Figure 61 Standoff Profile with 20 ft Spacing

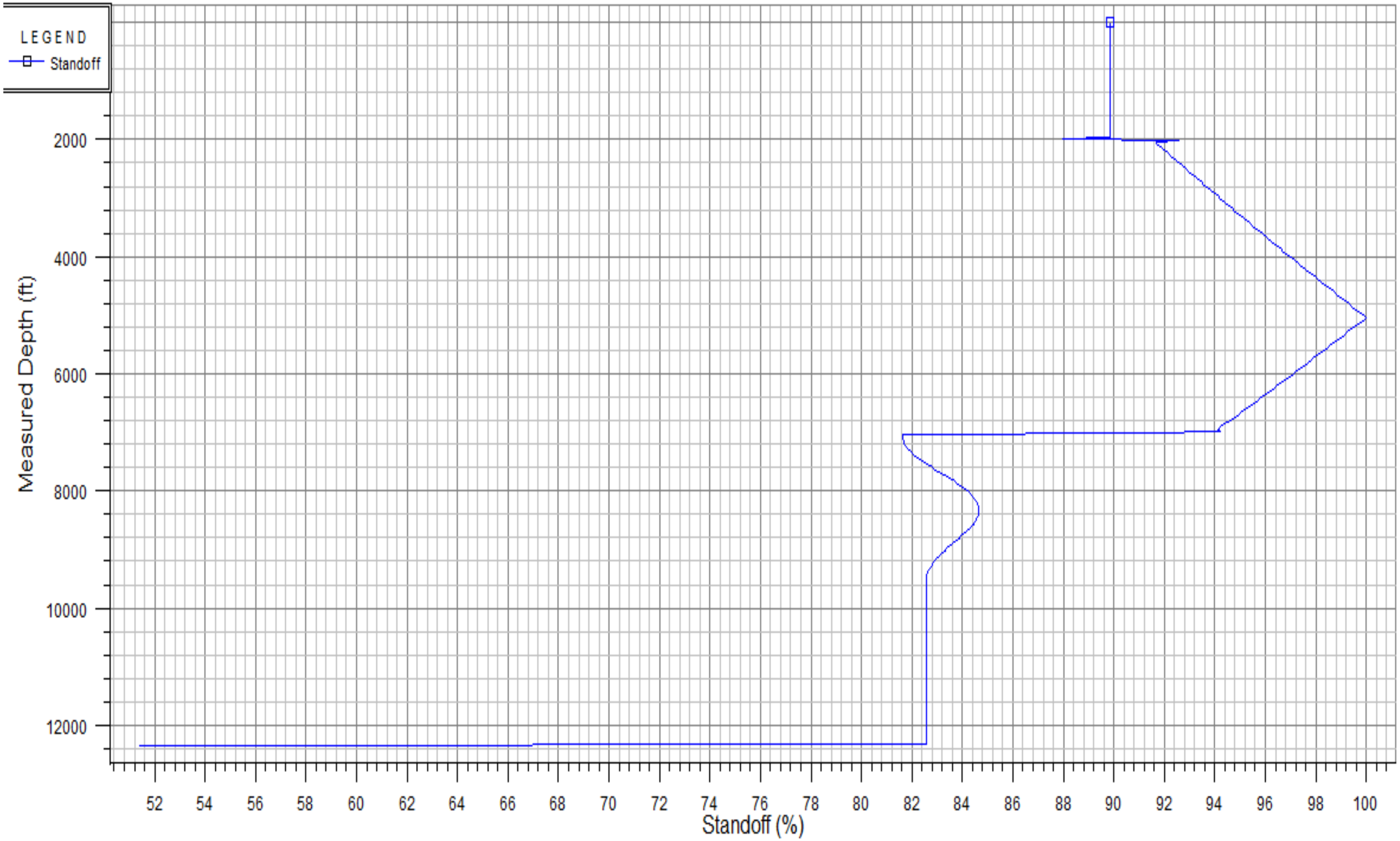


Figure 62 Standoff Profile with 30 ft Spacing

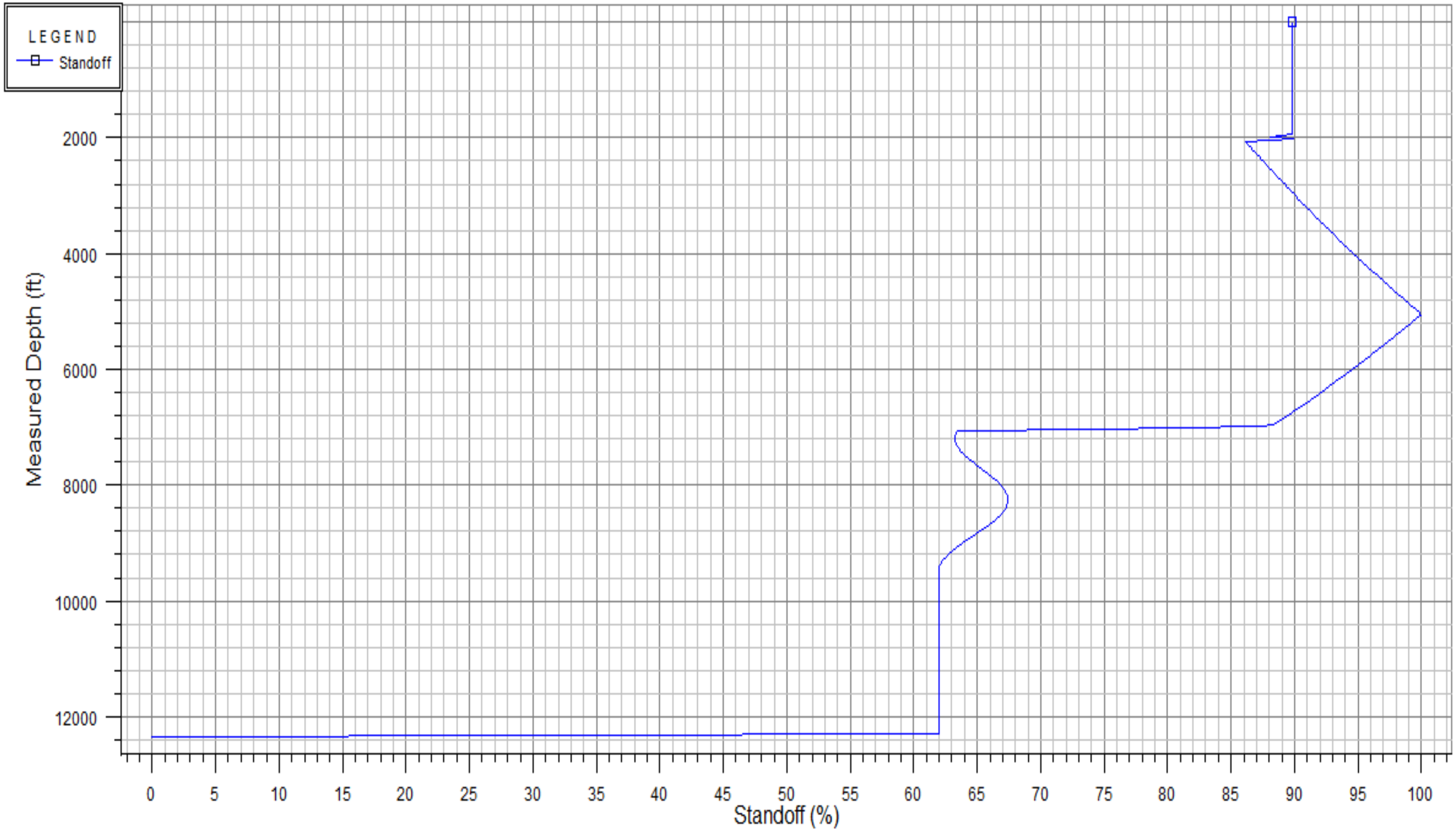


Figure 63 Standoff Profile with 40 ft Spacing

2.4.2.2 Specify Standoff

This mode of calculation is suitable for the conditions when the insufficient experience do not permit to select spacing. In this mode, standoff has to be specified and the program varies the spacing in along the wellbore to achieve that standoff. The disadvantage of using this scheme is that it yields a centralizer placement program which is difficult to follow. Table 6 shows how the number of centralizers increases with the increase in standoff requirement.

Table 6 Results with Specify Standoff Mode of Calculation

MAXIMUM SPACING (FT)	MINIMUM SPACING (FT)	SPECIFIED STANDOFF (%)	CALCULATED NUMBER OF CENTRALIZER
400	0	70	209
400	0	80	243
400	0	90	366

Figures 64, 65 and 66 shows the standoff variations with depth for the three cases mentioned in Table 6. In Figure 64, the requirement for standoff is not met due to less number of centralizers. But as the number of centralizers increase in other two cases, the standoff profile shifts towards the safe region.

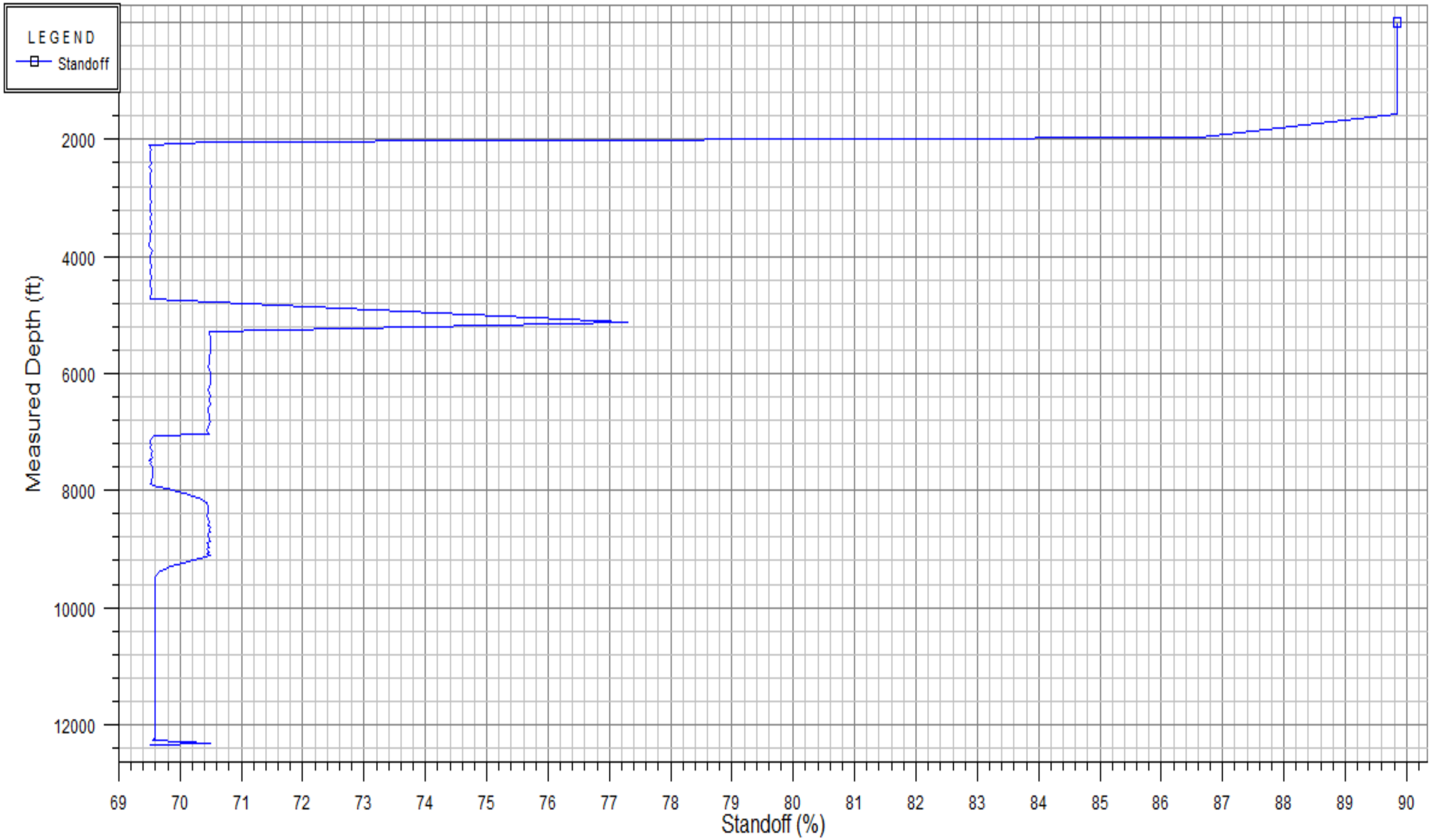


Figure 64 Standoff Profile with 70% Standoff

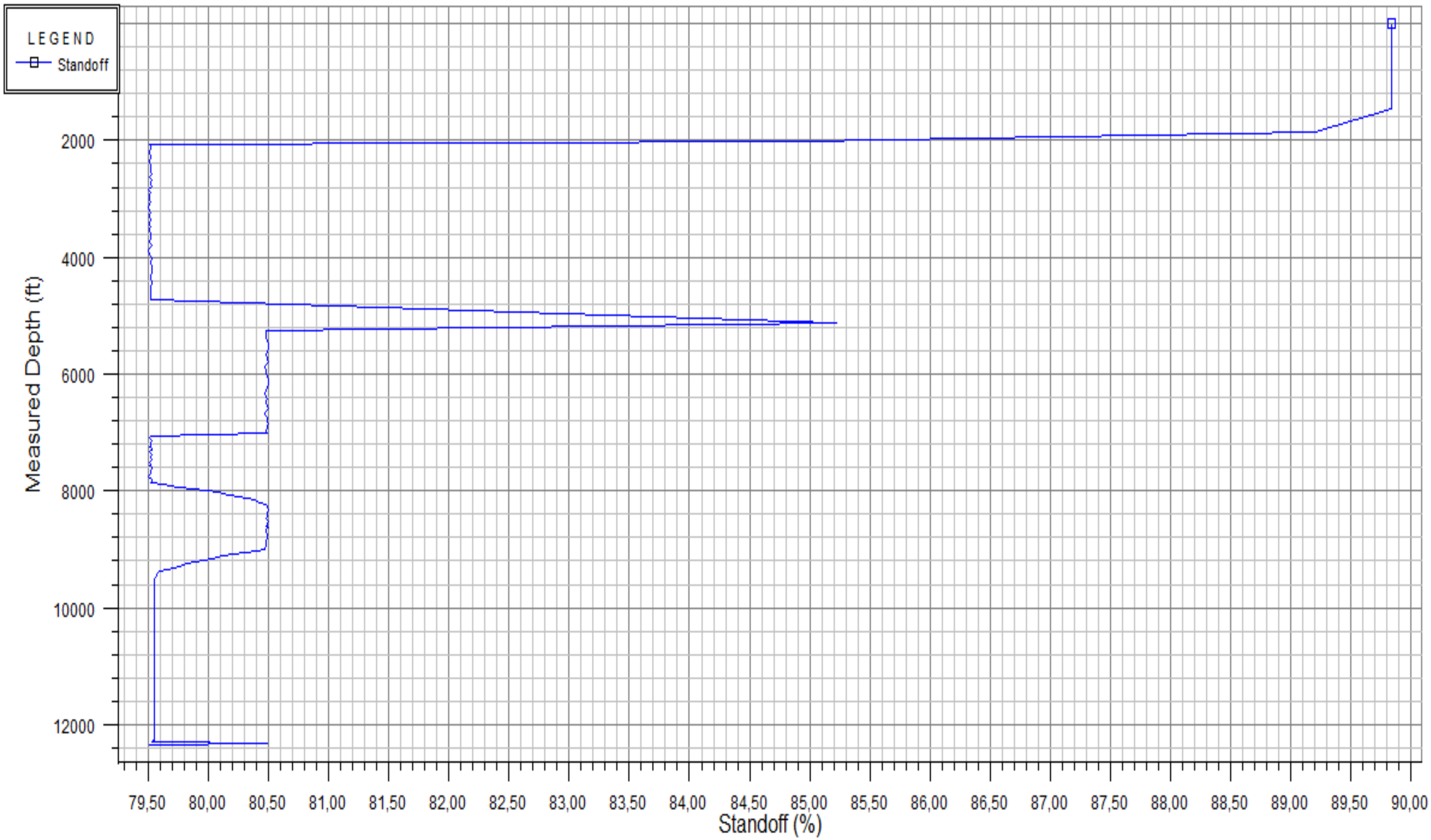


Figure 65 Standoff Profile with 80% Standoff

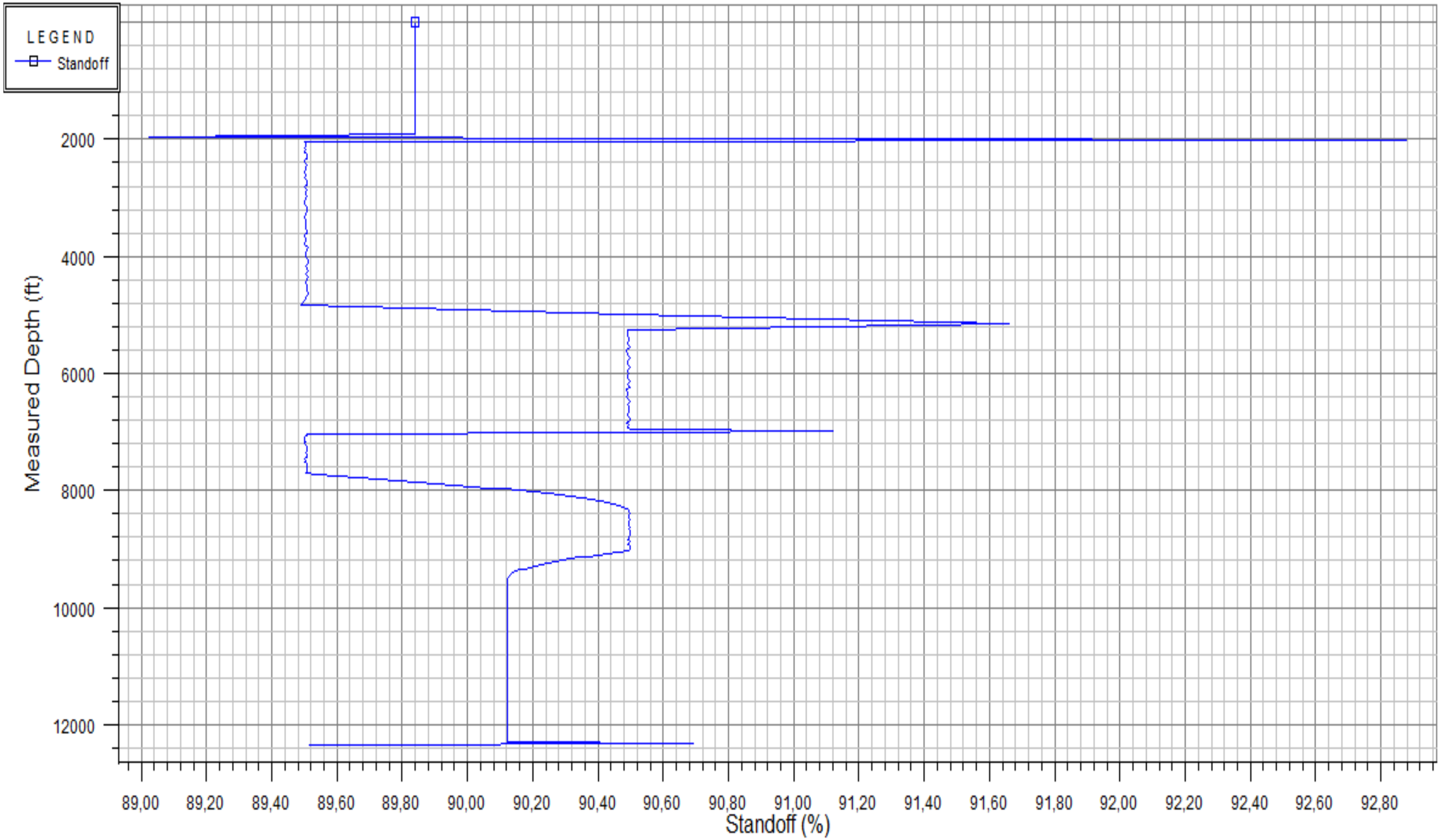


Figure 66 Standoff Profile with 90% Standoff

2.4.2.3 Optimum spacing

This mode is designed to give optimum placement solution. The spacing and standoff are selected so that both standoff requirements can be met as well as placement program can be easilyfollowedduring casing running. Brief summary of this mode is shown in Table 7.

Table 7 Results with Optimum Spacing Mode of Calculation

CASES	MAXIMUM SPACING (FT)	MINIMUM SPACING (FT)	SPECIFIED STANDOFF (%)	CALCULATED NUMBER OF CENTRALIZER
A	37	0	70	334
B	250	37	90	297
C	450	0	75	223
D	450	37	75	217
E	450	37	71	210

The plot between standoff and depth for all the cases is shown in Figures; 67, 68, 69, 70 and 71. The number of centralizers is optimized by selecting different combinations of spacing without compromising minimum standoff requirement of 70%. Figure 71 shows the final result with desired standoff and optimum number of centralizers.

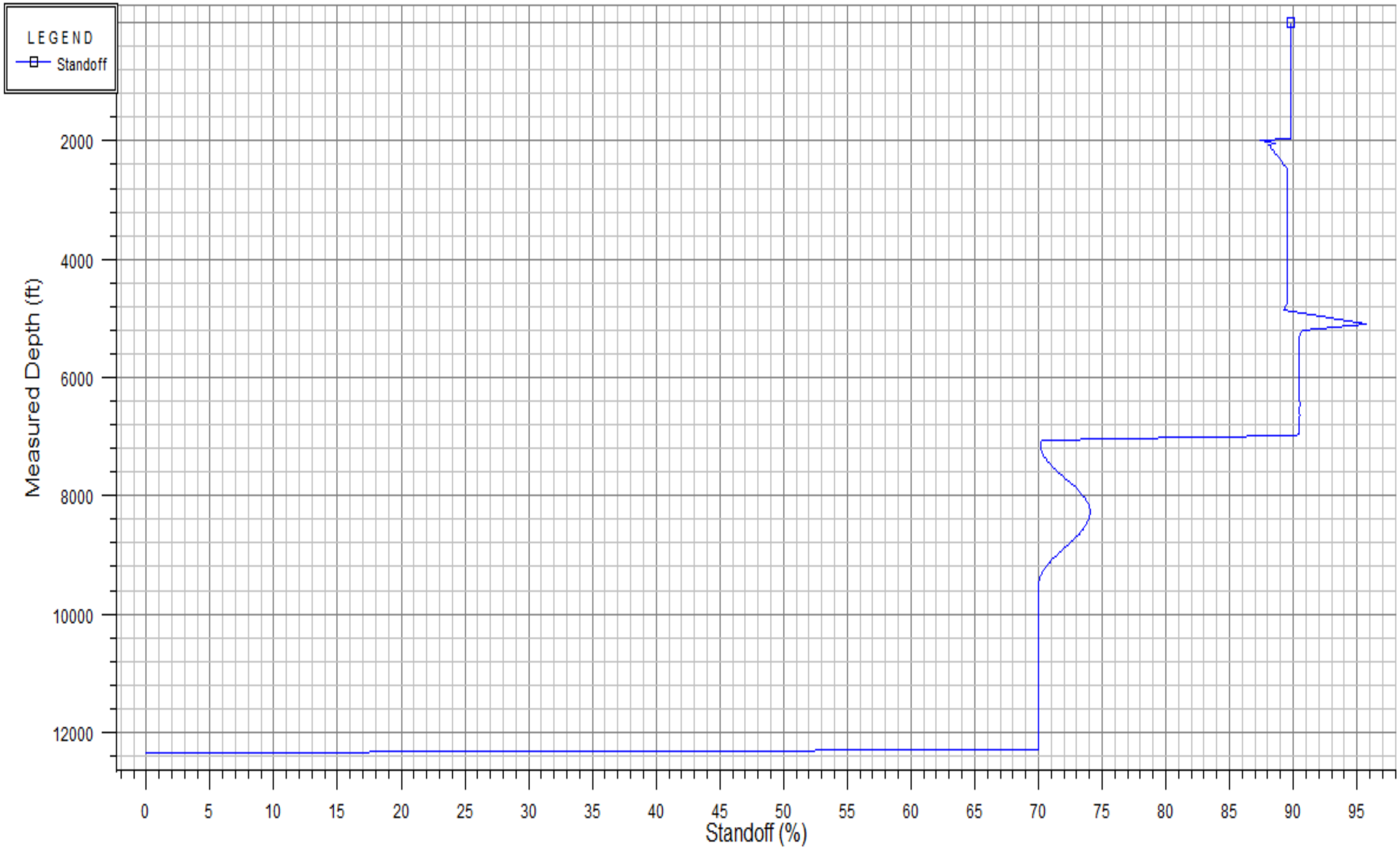


Figure 67 Standoff Profile of Case A

Figure 68 Standoff Profile of Case B

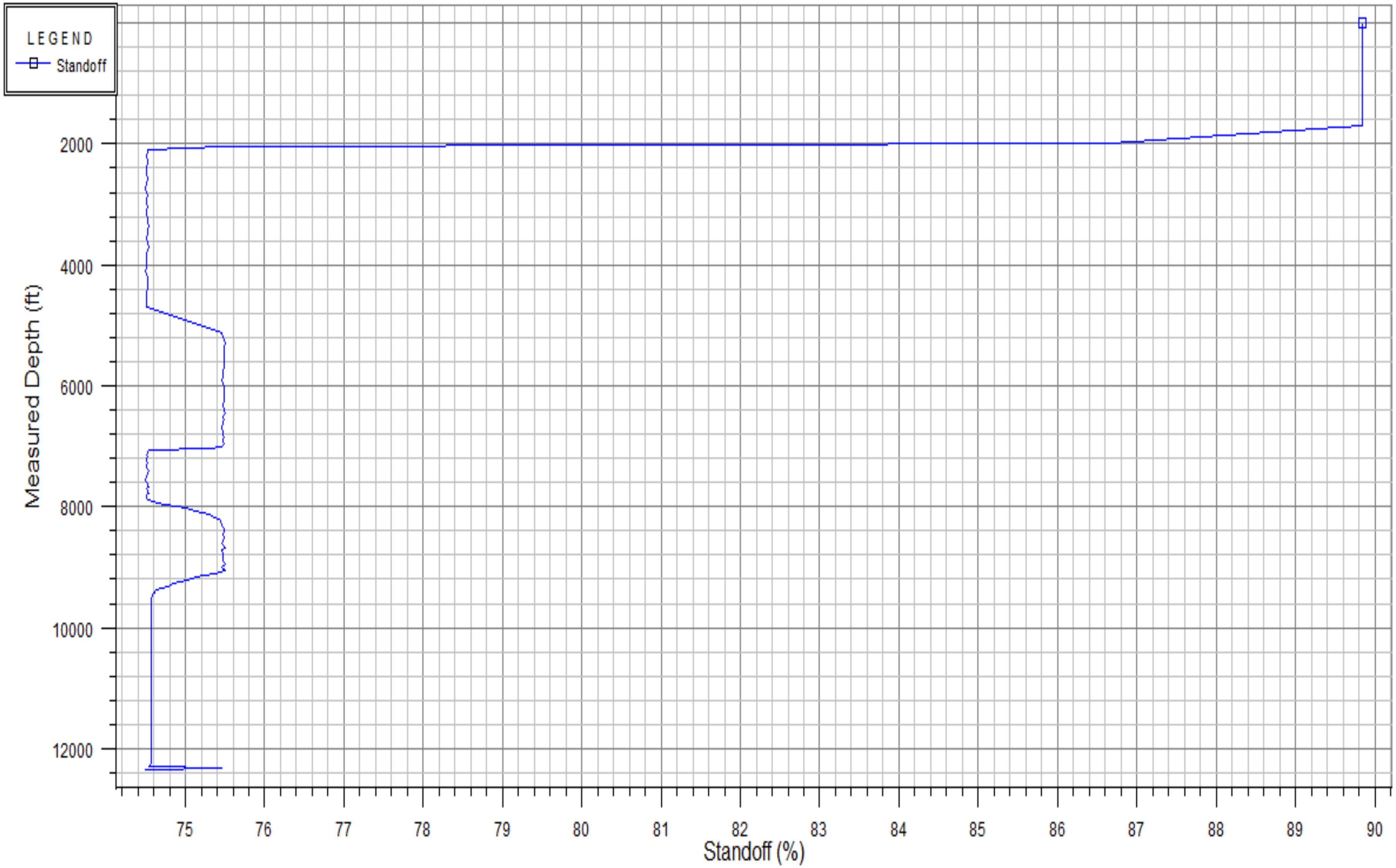


Figure 69 Standoff Profile of Case C

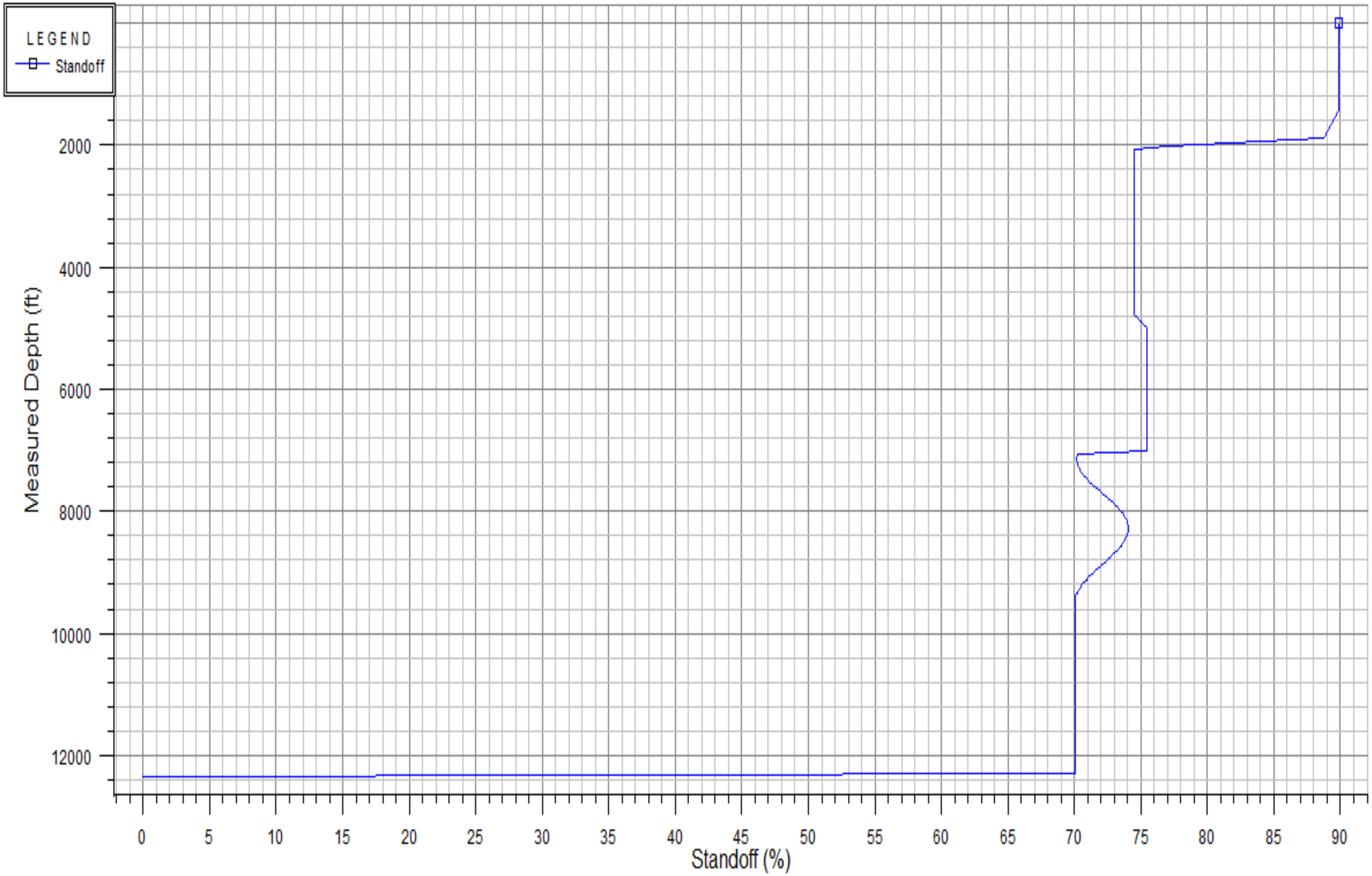


Figure 70 Standoff Profile of Case D

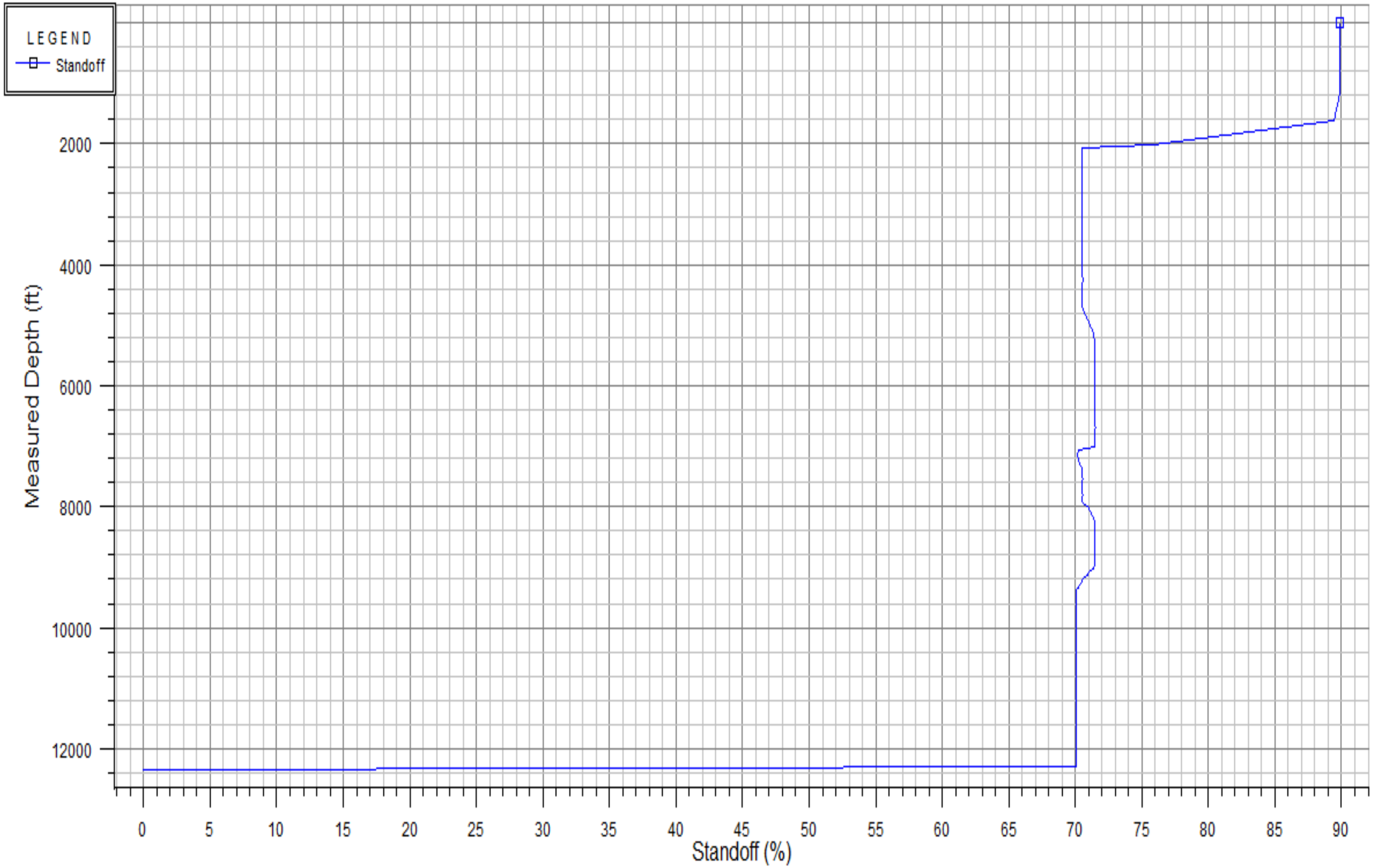


Figure 71 Standoff Profile of Case E

2.4.3 Cement Channeling

Channeling can occur when the casing is not placed in the center of the well. This leads to thinner annulus on one side and thicker annulus on the other side. The downside of this phenomena is that under cementing procedure, the cement will get higher in the thinner side, and parts of the thicker annulus will remain poorly cemented which necessitates a remedial cementing in most cases, thus more resources and time gets wasted.

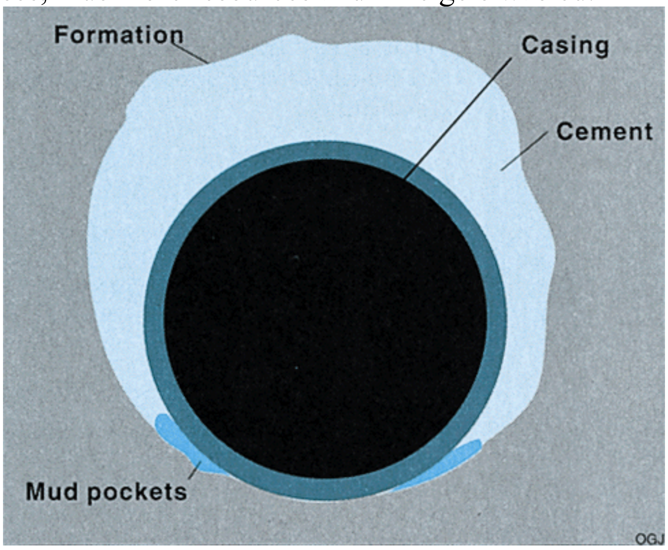


Figure 72 Cement Channeling [15]

2.5 Pipe Reciprocation and Rotation

Moving the string while cement is pumped helps to attain good cement quality and better wellbore integrity. Both pipe rotation and string reciprocation enhances the mud removal. Normally the casing is rotated at about 20-30rpm with reciprocation of 20-30ft [16]. This pipe movement allows breaking up the stationary, gelled pockets of drilling fluid as well as making the cutting free which got trapped in the gelled mud. High displacement efficiency can be attain at lower flow rates due to pipe movement [17].

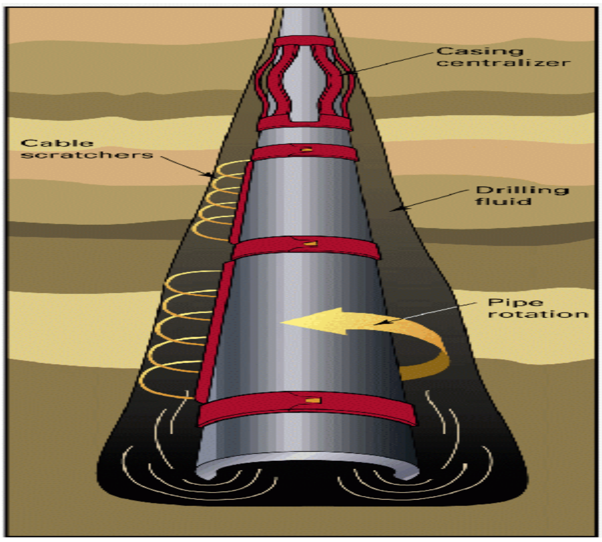


Figure 73 Rotation of Casing during Mud Conditioning [17]

Pipe movements allow circulating through poorly centralized flow paths and making the pipe well cemented even in those areas. If scratchers are attachedaround the casing, pipe movement give an additional benefit of removing mud cake thereby enabling a quality cement job. There are no industry standards specified for how much pipe movement is beneficial. Sometimes reciprocation is not recommended as it can exert swab and surge pressure which is critical especially in case of very narrow margin between fracture pressure and Equivalent Circulating Density (ECD). Different types of liner hanger have different requirements for pipe movement. Some of them allow while others have limitation for example non-rotating liner hanger [17].

2.5.1 Barriers to pipe movement

Although the benefits of pipe movements are quite clear and there are several studies and API recommendation on it, this technique is not used quite extensively in the field. Even in the US, only 6% of the total wells use the pipe movement during cementing in the era where we have advancement in rig designs, top drives, wellbore monitoring [18]. The important barriers are limited industry knowledge and hardcore status quo practices which take time to change.
There are several misconceptions which act as hurdle in way for implementing pipe movement during cementing. This section highlights few of them.

2.5.1.1 Pumping cement through top drive

Although majority of top drive manufacturers do not object cement pumping through top drive, there is a trend in industry to use cementing head during cement pumping. Sometimes it is said that the abrasive solids in cement can damage the top drive. This argument can be let down by highlighting the abrasiveness of solids in drilling mud [18].

2.5.1.2 Rotating the casing

There is a misconception that casing is not made to rotate. As long laterals in extended reach wells and shale applications are drilled, it urges the industry to develop casing connection with high torque rating which can equally be used in shallow depths. Casing while drilling application together with casing connection advancements have now enabled the industry to run the casing in the extreme environment by keeping the integrity of it [18].

2.5.1.3 Centralizer and Pipe Movement

Although the bow centralizers are not made for applications involving rotation, solid body centralizers are now allowing the operators to rotate the casing during cementing so that standoff can be kept close to 100%. Without pipe movement, immobile area is bigger and the chances of mud pockets are maximum [18].

2.5.1.4 Swab & surge Pressure

It is right to say that swab or surge effects can be developed if reciprocation is not properly applied which can further lead to well control issues. Therefore, planning of casing running speed is very necessary in order to evaluate swab and surge effect prior to operation. For narrow margins, only rotation can be used as solution [18].

2.5.1.5 Casing landing

In offshore application, pipe movement cannot be done once casing reaches bottom due to subsea wellheads or mud line suspension system. Enough rat hole and simple wellheads allow pipe movement on land wells. Torque and Drag analysis should be done for all rotating applications [18].

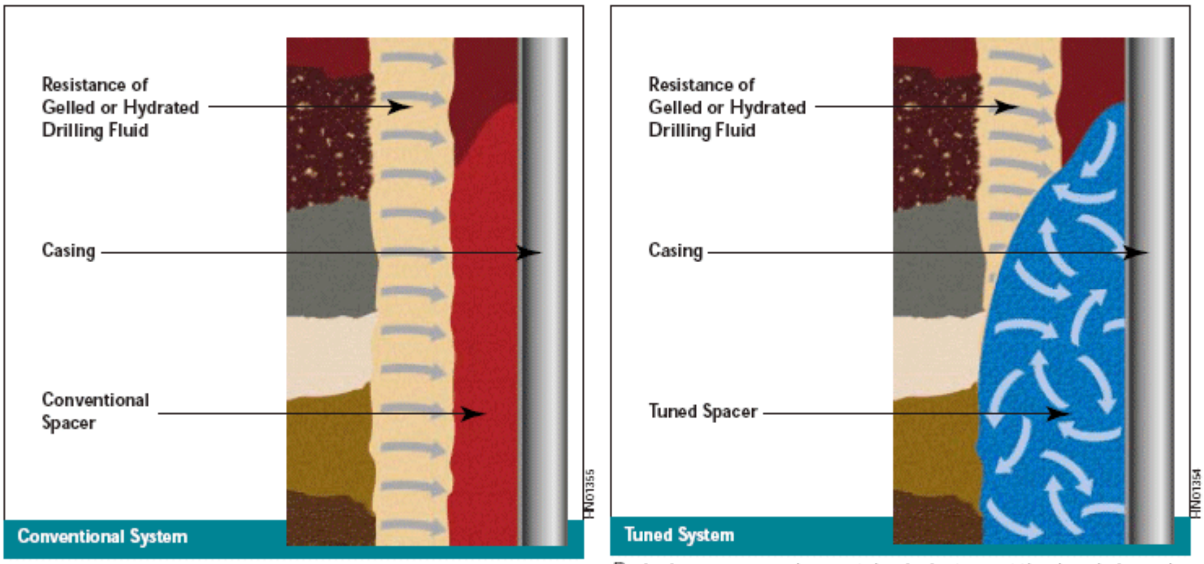
2.6 Use of Preflushes

Preflushes are the fluids used to prevent the mixing of drilling fluid and cement slurry as well as to help in mud displacement. Chemistry of preflushesis responsible for removing mud cake from annular wall. This is a small scale process which helps density and rheology of fluid in bulk displacement [2]. Preflushes should have compatibility with both cement slurry and mud, have required rheology and density to aid mud displacement and have sufficient chemical properties to make the surface as water wet.

Alteration in rock wettability and risk of formation damage should not be associated with preflushes. If a single preflush is not upto the mark, multiple preflushes can be selected in tandem [2].

2.6.1 Spacer

Spacers are a type of preflushes that is pumped before and after cement to avoid commingling of cement slurry with mud. It has specific rheological properties and density designed to achieve its objectives. Spacers should be compatible with cement and mud and they must not have excessive sedimentation. Some spacers are pumped with the purpose of well control (weighted spacers) while others are pumped to enhancemud removal (reactive spacers) [17]. Figure 74 shows how an efficient spacer design can completely remove the mud during pumping.



Gelled or dehydrated mud is difficult to displace. Channels can be created with thin spacers or slushes.

Designing a spacer and cement rheologies to meet the downhole mud conditions will more effectively displace the total wellbore mud.

Figure 74Comparison of an Properly Designed Spacer (Right) with a Conventional Spacer (Left) [19]

Spacers usually comprise of a viscosifier, dispersants, and fluid loss additives, weighting agents and surfactants. Due to high viscosity, spacers typically have laminar flow regime during its pumping in the well. Turbulent flow can also be achieved if their compositions have been optimized without putting its stability onstake. Spacer viscosity is a function of concentration of viscosifying polymer, weighting material, base fluid composition and downhole temperature.

2.6.2 Washes

Washes are a type of preflushes having density close to water or oil. Turbulent flow can easily be achieved through them. The working principle of washesare based on mud dispersion, tangential erosion of mud layers and making the surfaces of casing and formation as water wet surfaces. All this attributes are necessary for good cementing bonding.

Fresh water is used as a wash in case of water-based muds. Chemical washes are selected for more optimum results which contain surfactants and dispersants such as lignosulphonate. For application using invert emulsion drilling fluids, chemicalwash can either be consist of water, mutual solvents and surfactants or an oil wash which is then followed by water-based chemical wash. Laboratory testing is done to evaluate the type and concentration of surfactants (either anionic or nonionic). Chemical flushes such as sodium silicate based fluids and oxidizers have an ability to break drilling muds down and contribute in drilling fluid removal [17].

2.7 Select a Proper Cementing System and its Composition

Selection of cementing system is very critical and it must be based on objectives of job as well as requirements of well. Zonal isolation capability of cement does not only depend on higher compressive strength but also on other factors (Figure 75). A properly selected cementing system can withstand with the changing downhole environment and maintain the zonal isolation throughout the life of the well.

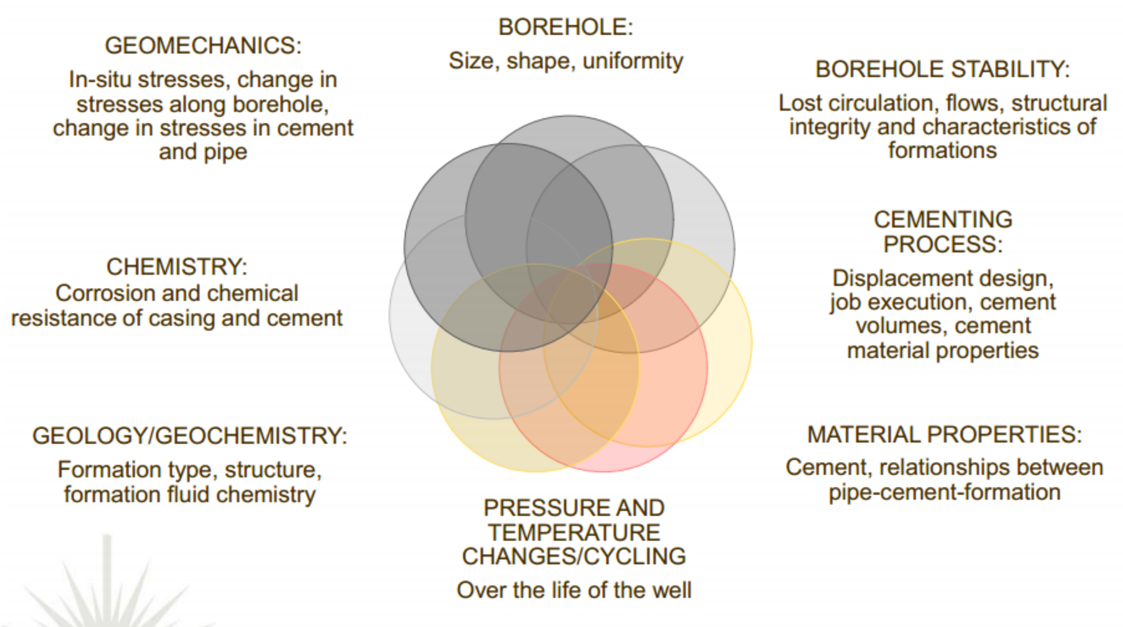


Figure 75 Variables affecting Zonal Isolation [20]

Fluid movement from one zone to another in annulusand high annulus pressure is the indicator of poor cementing job which can be due to insufficient properties. Study of wellbore stresses can also help in selecting better composition so that risk of cement sheath failurecanbe minimized. Casing expansion and contraction also affect the cement bonding due to induced stresses.

2.7.1 Types of Cementing Systems

There are different types of cementing systems that industry used to offer for different applications. These cementing systems should be analyzed for the well under study so that an optimized decision can be taken which will ensure better zonal isolation within the budget.

1. Deepwater cementing systems
2. Heavyweight cementing system
3. Lightweight cementing system
4. Self-healingsystems
5. Foam cementing
6. Corrosive gases resistant cementing system

2.7.1.1 Deepwater cementing systems

In deep water, conductor and surface casings offer a high risk in cementing because of an environment which is challenging from both technical and logistical perspectives. In order to achieve required zonal isolation and specifications for deep water, these challenges have to be addressed in designing cement slurry. In deep water environments, there is always a potential for shallow water and/or gas flow. During cementing, these flows create problems and put the well integrity in danger as subsidence can happen due to the flow. Structural casing buckling will then affect the wellbore integrity which will lead to the loss of the well. The cementing system for deep water applications should have all the characteristics to stop the flow of shallow water/gas especially rapid development of gel strength and low viscosity. Since the deep water environments are characterized by their low-temperature environments along with unconsolidated formation nature, high early compressive strength help to ensure wellbore integrity.

2.7.1.2 Heavyweight cementing system

High-pressure formations create a challenge for the cement as the cement density has to be high enough so that the hydrostatic pressure of cement would be higher than the formation pressure. The upper bound on cement density is dictated by the formation fracture pressure. Higher density of cement also aid in displacing the mud and reducing the contamination risk. Heavy weight cementing system should be selected if the formationis categorized as high pressure. This system prevents the formation fluid to enter into cement column and helps to eliminate the risk of remedial cementing. The density of these systems can be taken up to 22 lbs/gal [21].

2.7.1.3 Lightweight cementing system

Depleted zones always bring new challenges for the cementing operations as the low formation pressure is not capable enough to balance the hydrostatic of cement in the annulus. Light weight cement system makes sure that the density of the cement is kept at minimum level so that the losses to the formation can be avoided. At the same time, cement should be capable enough to provide good compressive strength necessary to maintain well integrity. The cementing system utilizes the use of water, gas or low density particles into the cement to keep it less dense. This cementing system can also eliminates the multistage cementing job which is done to avoid high hydrostatic pressure at the formations.

2.7.1.4 Self-healing systems

The cement is subjected to various loads after being set such as drilling, stimulation, perforation, production and abandonment loads. Due to these loads, the cement can get damaged and result in formation fluid cross flow, casing pressure at surface, casing vent flow, collapsed casing or contamination of water zones. These loads are different from gas migration and other conventional cementing issues as cement is subjected to them after being set. Besides these, there are few other stresses that the cementis subjected to such as thermal effects, casing expansion and contraction. These cement system has a built-in capability of repairing the cracks and thereby maintaining its integrity without any remedial operation. Long life cement sheath and better zonal isolation are the major benefits that a self-healing cementing system uses to deliver.

2.7.1.5 Foam cementing system

This cementing system comprises of cement slurry, foaming agent and a gas. This system can be prepared by adding a gas, typically nitrogen, into base cement slurry at high pressure that contains foam stabilizer and foam agent. The resulting slurry is very stable, light weight which resembles like gray shaving foam. On mixing and shearing, tiny and discrete bubble get created which are not interconnected and form a less dense cement matrix with the characteristics such as high strength and low permeability. All types of well can be cemented using foam cementing [22].

2.7.1.6 Corrosive gases resistant cementing system

CO_2 and H_2S create a highly corrosive environment to cementing system. It compromises the well integrity due to the leakage of these corrosive gasesto surface. The cementing system should be designed with the properties necessary to keep those gases in the formation and prevent their interaction with cement. This type of cement also finds its application for CO_2 storage and CO_2 injection applications particularly in enhanced oil recovery method.

Besides these cementing systems, following features should also be analyzed while selecting proper cementing system depending upon the application.

- Gas migration control
- Lost circulation mitigation
- Solutions for underground gas storage
- Heavy oil and geothermal wells cementing
- Remedial cementing

2.8 Gas channeling

During cement setting, a contraction-expansion mechanism occurs and this may sometimes lead to poor bonding between cement and formation, leading to intrusion of gas into the cement and leakage of gas to the surface. This phenomenon gives environmental safety hazards and is very expensive to cure. Squeeze cement is usually used to solve the problem, but it doesn't give a permanent solution. Gas leaks into the cement, during and after setting. When the cement is in liquid state in the annulus before setting, the hydrostatic pressure is high and prevents gas from migrating into it. As the cement which is in contact with the permeable formation sets earlier than the rest of the cement in the annulus, the cement column looses total hydrostatic pressure which allows gas to migrate through it. Type of cement and additives used play important role in this case. It may happen that the cement doesn't displace the mud in the annulus properly, and mud cake remains between the cement and the formation, this forms a week zone for passage of gas through it. In fact, this is the reason for many cementing jobs failures [23]

There are basically three main passages for the gas to migrate through,

1. Through the voids of mud cake which occurs as a result of improper design of spacer and thus poor mud displacement (Figure 76).

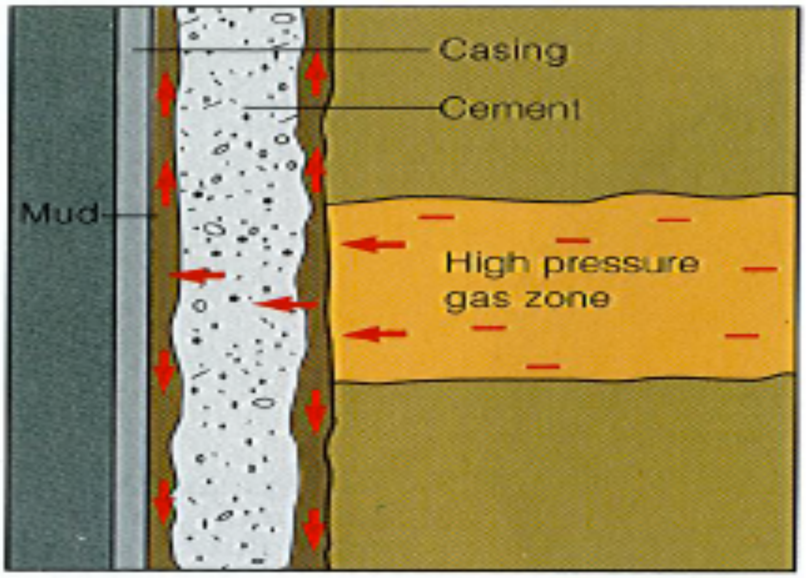


Figure 76 Gas Migration though Mud Cake [24]

2. Through microannuli between cement-formation and cement casing. This is due to contraction-expansion mechanism during cement setting (Figure 77).

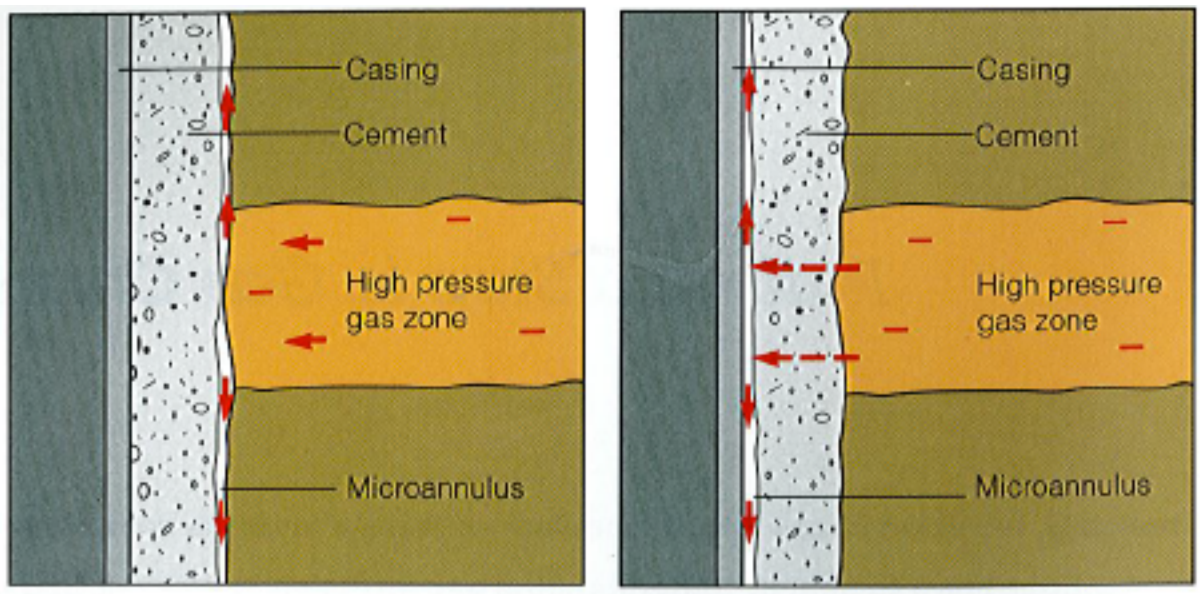


Figure 77 Gas Migration though Microannulus [24]

3. Through “matrix gas channeling”, which is through the cement itself this time.This happens when the cement naturally creates microvoids through which the gas can migrate (Figure 78).

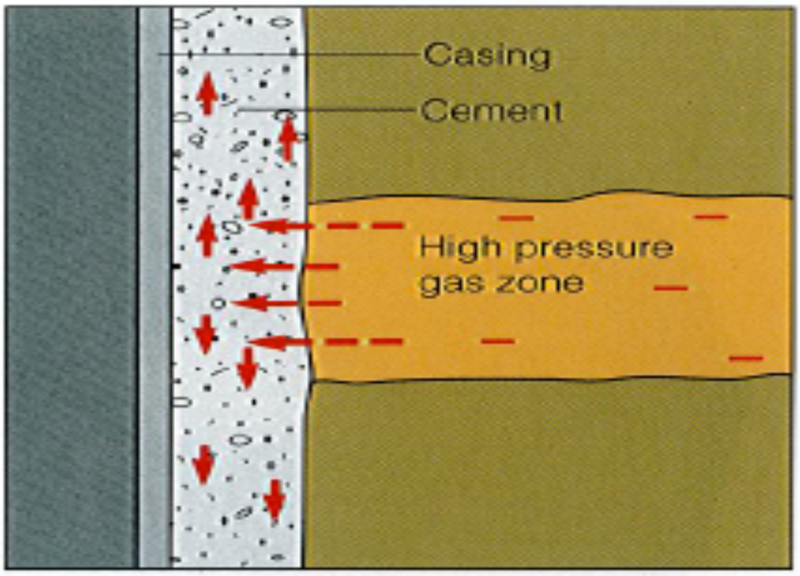


Figure 78 Gas Migration through Matrix Gas Channeling [24]

Adding 2.5-6% by weight of anchorage clay to the cement at a temperature of 93.5° Celsius to overcome the shrinkage problem and the void resulted by that which leads to gas migration. Adding 4-8% by weight of a class of synthetic rubber powder eliminates the migration of gas through the cement itself, it seals the microvoids occurring within the cement during setting. Ironate sponge has also shown good results according to the same research, ironate sponge addition to the slurry delivers better bond to the casing due to higher magnetic field of ironate sponge under higher temperatures of deeper formation [23].

3 NEW APPROACHES TO REDUCE TIME AND COST DURING WELL PLUG AND ABANDONMENT

3.1 Introduction to Well Plug and Abandonment

When the logs indicate that remaining hydrocarbons in the reservoir are not sufficient enough to continue the production operations in a commercial way or when the reservoir is drained after production operations, it is vital to permanently plug the reservoir in order to isolate the reservoir, otherwise drinking water could get contaminated and hydrocarbons could leak to the surface.

Caprock was the natural seal for the reservoir before drilling and production, so the goal here would be restoring the natural sealing ability of the formation. This requires proper and accurate plan by engineers for the cementing procedure. Well abandonment comprises of different phases such as; reservoir abandonment, intermediate abandonment and wellhead and conductor removal. Each of these phases has its own challenges. Different approaches have been developed during the last years in order to overcome challenges and ensure economical, safe and less time-consuming abandonment. Onemajorchallenge during plug and abandonment is removing of the production tubing to the land before placing the cement plug, this to ensure good bond between the formation and the cementplug. Removing the production tubing requires though a rig which has a very high daily cost rate to rent and the removal process is time-consuming.

Plug and abandonment is a very expensive phase, for example, to plug all Norwegian wells permanently will cost around 875 billion NOK. As new technologies arrive to make it possible to leave the production pipe in the hole instead of pulling it out before cementing will give exciting results related to cost and time.

Aarbakke Innovation are developing technology for effective plugging of the well. This technology will eliminate the need of pulling out several kilometers of production pipe out of the well before cementing. This technology makes it possible to use light vessels instead of rigs to plug a well. They have developed a tool which is run down the well. This tool will make it possible to seal the well properly with the production pipe left inside [25].

3.2 Saving cost and time with new P&A procedures

While Aarbakke Innovation has developed a tool to make it possible to plug the well properly with the production tubing left in the hole, DrillWell Research Centre conducted in 2016a research about cement placement with tubing left in the hole during plug and abandonment operations. No special tool was used in with their research, they approved that cementing during plug and abandonment can be performed with the production tubing left in the hole. This can save a huge amount of time and cost. In such procedure the pumped cement must displace the mud fully in the planned point for the cement plug in order for the cement-bond to be good enough. The research was also performed with the control lines attached to the tubing to see how it affects the bonding between the cement and the tubing. Assemblies with 7” tubing inside 9 5/8” casing were used for the research. Conventional cement was used for one experiment and expandable cement was used for the other [26].

Table 8 Test Assemblies Used for the Test

ASSEMBLY #	CEMENT TYPE	CONTROL LINES
Conv-A	Conventional	No
Conv-B	Conventional	Yes
Exp-A	Expandable	No
Exp-B	Expandable	Yes
Exp-C	Expandable	Yes

Conventional class G cement with density of 1.92 s.g. was pumped through the tubing and down through perforations on the lower end of the tubing and upward to displace the 1.2 s.g. brine in the annulus. In the formation the cement is in warm conditions under curing, for this purpose, the casings were covered with rockwool to keep the cement warm under curing time simulating real conditions. The assemblies were 36 m in length ConvB had two control cables attached to it while ConvA was without control cable, an offset of 2.6 cm were created due to the cable clamps and 1.1 cm due to the tubing collars [26].

Cement placement quality was evaluated by cutting the cemented pipes after cement setting and inspecting the cement-bond. Pressure test with water injection was also performed for quality test. Sensors were placed on the water channels. Pressure sensors were used to measure the pressure in the different points, and leakage and pressure drops were noted. The test assemblies were inclined with 85°.According to Figure 79 after 36 hours of curing time the cement reached a maximum temperature of 75°C [26].

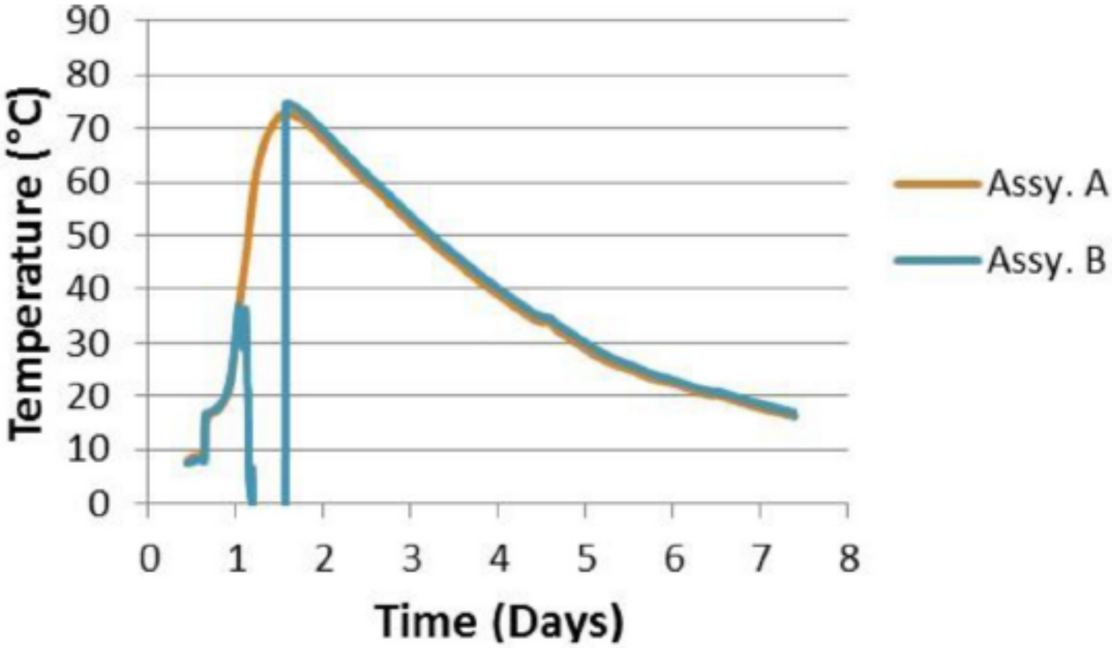


Figure 79Conventional cement curing time for Assembly A and B [26]

The assemblies were left about one week for curing, flow tests with 50-100 bar inside the casing were then performed. PT1-PT6 are pressure sensors (Figure 80). Water injected through PT1 and channeled through PT3 and pressure was calculated through all the pressure sensors. PT2 and PT4 read almost the same pressure, so we assume that PT3 and PT5 did the same. This shows that there was good pressure connection in the annulus due to shrinking of the cement in the annulus. The friction factor along the annulus led to different pressure readings along the assembly [26].

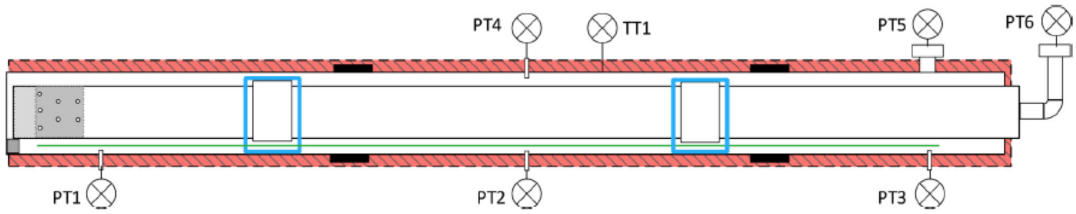


Figure 80Assembly with conventional cement. Green line represents the control cable, blue rectangles represent cable clamps, PT1-PT6 are pressure sensors and TT1 is temperature-sensor [26]

The test above was for conventional cement. For expandable cement EXP-A, EXP-B and EXP-C were used. These assemblies were shorter in length, they were 12 m long. The inclination remained the same.

EXP-A was with no cables and flat cables were strapped to EXP-B and EXP-C. No clamps were used for these, instead, the control lines were strapped to the high side of the pipe. Heating cables were also used for expandable cement, theywere placed under the rockwool layer. In all of these tests the cement was pumped slowly for better displacement of brine. Same cement density, but 1.0 s.g. waterwas used this time.The dehydration process of the cement leads to higher temperature which helps to increase the speed of setting of the cement.

For expandable cement, heating cables were turned on to increase the initial temperature to get close to the usual formation temperature, the heating cables increased the temperature of the pipes to 90 °C and turned off, the dehydration increased the temperature to 110 °C. To simulate a stable formation temperature, the heating cables were turned on again after the temperature had sunk to 90 °C and kept it at that temperature [26].

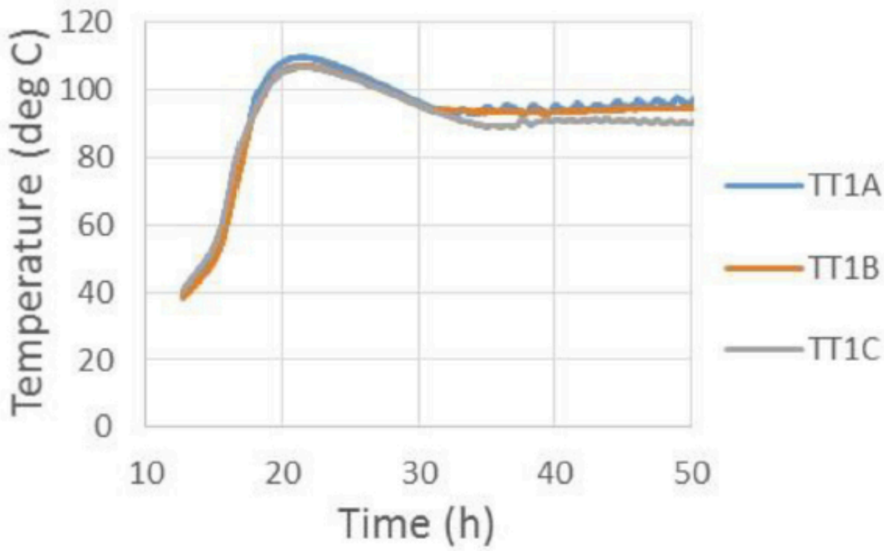


Figure 81Temperature development for expandable cement at 20 bar Pressure [26]

Since the cement was at higher temperature, the flow test water was heated to match the cement temperature to avoid cracking the warm cement. The expandable cement needs more time in order to expand properly. For this procedure3 weeks were allowed for that, more time is needed for full expansion. The leakage path between casing and cement was very small but was still measured to ensure safe plug and abandonment. This space is measured in micrometers. This microspace is considered uniform in order for the calculations to be applicable, but in reality they are not uniform. The flow of the fluid caused the casing to expand and the cement to contract leading to a space between the casing and the cement and creating a “inducedmicro annuli” while in the conventional cementing the cement has a shrinking effect which also creates a space which is called “permanent micro annuli”. In the calculations of the micro-annuli, both are taken into consideration, i.e. effective micro-annuli is considered. Space between cement and the casing was calculated through the pressure drop during injection of water with different pressures. The calculations input is pressure drop and the result is a rough measure of the geometrical space available between the casing wall and the cement [26].

3.3 Result of the test:

After 8-9 days of curing time for the conventional cement, the flowtests were performed. Both assemblies gave almost the same result. As result of flow tests, casing expansion and cement deformation occurred. As Figure 82 shows, the microannuli were induced both the casing and the cement. Pressure drop between PT1 and PT4 didn’t exceed 4.5 bar during the test. We can note through the Figure 82 and 83 that the pressure drop is smaller than usual, the reason is that PT3 is at downside, and due to weight, cement can pressurize against the port, narrowing down the opening which reduces the flow out, creating a slight backpressure at PT3, therefore the difference between the inlet and outlet pressure is less [26].

Pressure PT1	Pressure PT1-PT4	Leakage point	Leakage	Calculated microannulus	δR induced casing	δR induced cement
(bar)	(bar)		(ml/min)	(μm)	(μm)	(μm)
54	0.5	PT3:	14	65	28	8
93	2.5	PT3:	95		48	14
56	3.5	PT3:	16	56	29	8
		PT2:	40			
94	4.5	PT3:	43		48	14
		PT2:	93			

Figure 82 Calculated Microannuli [26]

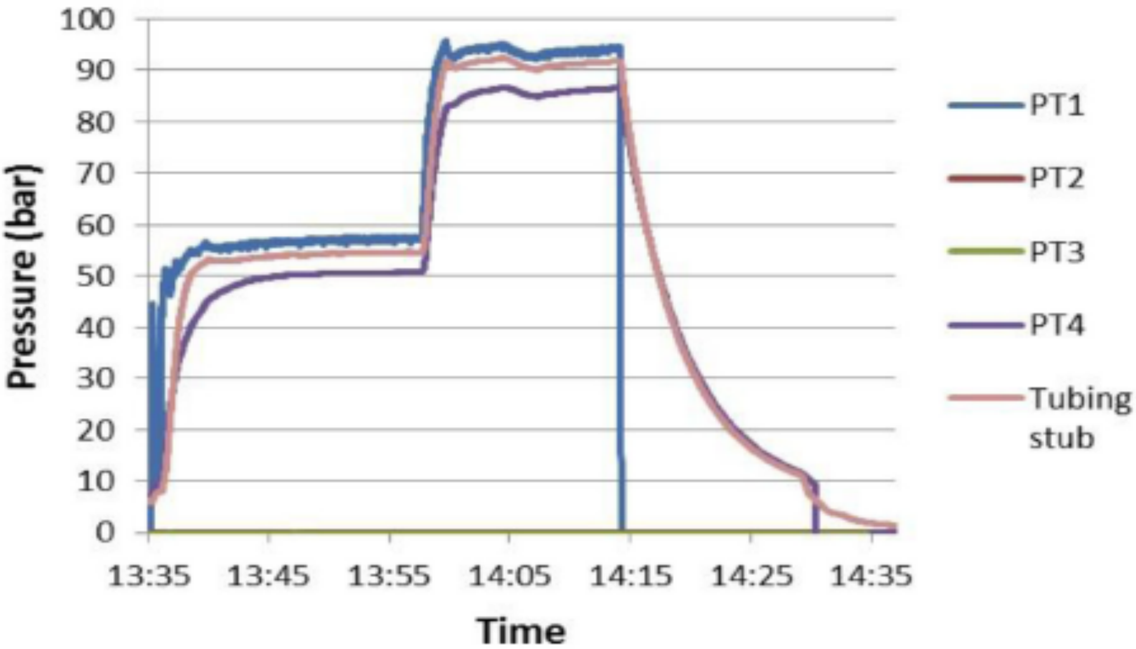


Figure 83 Pressure sensor readings for different flow measurements for Conventional cement water though inlet PT1 and outlet through PT3 [26]

Figure 84 is from the expandable cement test. It represents the assembly C but all assemblies gave same results. Flow measurements through PT1 and out through PT4 and PT6 are indicated in Figure 85. As the figure shows, 11:02-12:30 fluid leaked from PT6. The upper half pressure drop is measured by subtracting PT5 value from PT3 value. Similarly, the pressure drop for the lower part was measured [26].

Pressure PT3	Pressure PT3 - PT6	Leakage	δR induced casing	δR induced cement	Calculated microannulus
(bar)	(bar)	(ml/min)	(μm)	(μm)	(μm)
125	48	98	44	15	22
126	48	94	44	15	22
127	49	92	45	15	22
96	50	49	32	11	18
95	51	48	31	10	17
66	47	23	19	6	14
65	44	23	19	6	14
42	30	13	9	3	13
42	30	13	9	3	13

Figure 84 Calculated microannuli in assembly C (Expandable cement) [26]

As we can see the tables above indicate micro-annuli and leakage, but these leakages are not high enough to create a concern for failure, since the cemented area is usually several hundred meters. So in real life, this wouldn't give any negative results [26].

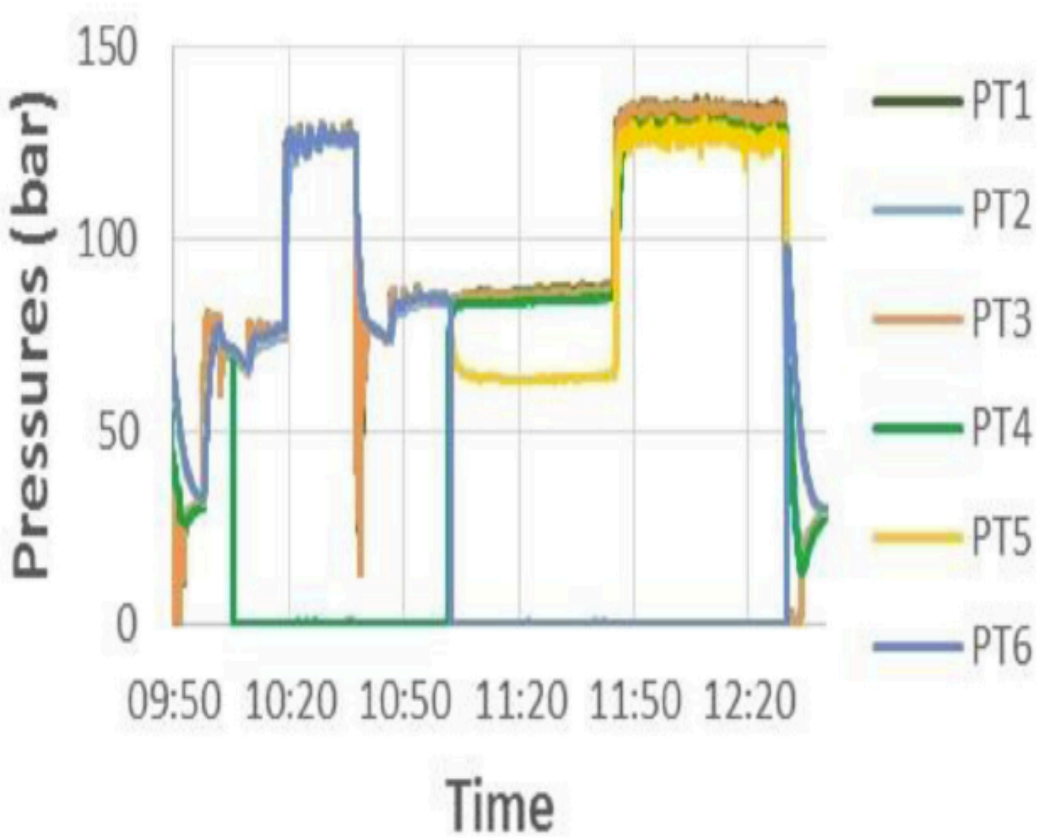


Figure 85 Pressure sensor readings for different flow measurements for expandable cement water though inlet PT1 and outlet through PT4 and PT6 [26]

In addition to pressure drop measurements, the assembly was cut through several places to check the displacement quality. Even though the control lines were attached, the cement displacement was very good with no missing parts or gaps. Inaccurate centralization didn't affect the cement placement quality either [26].

Figure 86 Pipe cemented inside casing with expandable cement and with attached control lines [26]

There are different sealing abilities for different fluids, to check sealing effect, flow test with light oil was also performed. Light oil was injected through PT1 as usual and outlet was PT5. Injection had to be above 80 barin order to see any flow at all with light oil. With light oil the flow was much reduced compared to water flow out. This could be caused by the capillary effects. The pressure readings from the sensors wasgenerally proportional to the flow rates with expandable cement except for PT3 in the middle, which seemed to read less proportional values with increasing flow rate. It was proportional up to 80 bar flow rate, after that it decreased slightly, the reason is that the induced microannuli started occurring after increasing the flow rate, before that, there was only permanent microannuli which was not related to the flow rate. The explanation behindthis phenomenon is that as more annulus occurs less pressure builds up in that section [26].

3.4 Conclusion of the tests:

According to these tests, leaving the tubing in the hole will still give good results of sealing the well permanently when it comes to plug and abandonment. Even attachment of control lines and lack of centralization doesn’t affect the quality of cement placement. For these tests 1.2 s.g. and 1.0 s.g. brine were used as fluid to be displaced by cement, however on the field, the drilling fluid could have different properties which may affect the results.

Even though the expandable cement was heated under the test, and there was less temperature differences compared to conventional assemblies, the results indicate that the expandable cement is more useful, it gives better results than conventional cement, better sealing is obtained from the expanding effect [26].

4 SOLUTIONS AND DISCUTSSION

This chapter presents the solutions and methods that can be used in oil well cementing operation both in the planning, execution and evaluation stages in order to save precious rig time. The areas of improvements, highlighted in the previous chapter are being the focal point in this chapter with some other pragmatic approaches that can also be adopted.

4.1 Adopting Compressive Strength of 500 psi

Compressive strength of 500 psi is the recommended cement strength by API before continuing drilling of the next section. The time required to reach this value is suggested by API to be 8 hours. According to the tests shown in chapter 2, 8 psi tensile strength which corresponds to 100 psi compressive strength is actually strong enough to hold the casing while drilling the next section in most operations. The problem is though that the initial setting time for cement is also around 100 psi, so the time difference between sufficient compressive strength and initial setting time of the cement is too low. This is one of the reasons why 500 psi and a minimum of 8 hours are values that are suggested by API standards, this to avoid the possibility that the cement may not be set at all because this would lead to collapse.

API suggests that 250 psi is the minimum compressive strength and 500 psi is recommended. 500 psi is used by most of the companies without knowing that the cement may be already set hours before and is “waiting” for drilling of the next section. 500 psi is too much and according to the tests represented in chapter 2, 250 psi is safe to adhere to. The time suggested by API to reach 500 psi is according to the tests also too much. Figure 2 shows that when the temperature is above 30 Celsius, the time required to reach 500 psi compressive strength is 3-6 hours related to different cement classes. While time required to reach 250 psi under same conditions were 3-5 hours. Using 250 psi instead of 500 psi and waiting the correct amount of time, can save us 2-4 hours.

4.2 Borehole Quality

The quality of borehole greatly affects the time that is going to be spent during cementing in the future. Drilling operation should always ensure that the borehole will have smooth wall and diameter equal to bit diameter. Selection of bit with adequate aggressiveness can play a vital role in improving borehole quality which can be made better with good drilling practices. Special additives such as clay inhibitors can be added to avoid clay swelling due to hydration which eventually alters hole quality.

Low dogleg severity should be selected during planning stage if possible. It will minimize the risk of casing being not in the center of well and the casing/hole annulus will be homogenous throughout which will ensure better primary cementing job and will save the time of remedial cementing.

Before starting cementing operation, the well bore should be stable and should not have suspended drilling cuttings. Adequate flow rate during drilling followed by sweeps of high viscosity pills can help in cleaning the hole properly, allowing cement bond free of contamination. Shaker monitoring will also help to analyze hole cleaning efficiency.

4.3 Wiper trips

Wiper trips should be performed after a particular interval of drilling. The interval should be based on past drilling experience, current well condition, company's wiper trip policy and economics. After reaching to casing point, wiper trip should be performed to evaluate borehole quality and necessary actions should be taken so that casing and cementing operation would not have any risk of downtime.

4.4 Mud Rheology

The rheology of drilling fluid has a great impact on proper removal of mud from well during cementing. Major rheological properties such as YP, PV and gel strength should be reduced to facilitate the displacement process. Density of mud can also be decreased to a certain level which should not compromised controlled wellbore situation. All these modification should be done after confirming that the well does not have suspended cuttings. These changes in rheology will properly displace the mud and will save rig time that can be spent on remedial cementing if some part of well remains un-cemented due to mud pockets.

4.5 Casing running

Casing trip-in speed should be analyzed for surge pressures so that the bottom hole pressure does not exceed formation strength. It will minimize the risk of cement loss during the job.
While running casing, circulation should be performed after every pre-determined intervals to break the long duration of static nature of mud as well as to clean any debris, generated due to casing running.

4.6 Batch Cementing vs. Fly-on Cementing

Considerable amount of time can be saved by adopting batch cementing especially for small and critical jobs due to better control on properties of slurry which definitely results in good cement quality and provide excellent zonal isolation. This willdefinitely reduce the probability of remedial jobs and leads to cost and time saving.
Large jobs such as cementation of intermediate and production casings should be perform using fly-on cementing technique so that continuous supply of cement slurry remains available at all time during the operation. Properties of slurry such as density should be monitored carefully by the operator on real-time density panel and adjustments should be made accordingly. Although fly cementing also provide good cement quality if carefully executed but in order to ensure excellent quality of cement against vulnerable zones, fly on cementing can be combined with batch cementing and job should be executed in a way that these zones receives slurry, prepared in the batch mixer.

4.7 Pumping Speed

Pumping rate during cementing is very vital as it directly affects the time. Selection of pumping rate should be done by evaluating cementing unit capability, effective displacement of cement and window between pore pressure and fracture pressure of the formations that are going to be cemented. Commercial software and field experiences should be used to perform sensitivity analysis with pumping rate and an optimized rate should be adopted which satisfies both economics as well as well integrity.

4.8 Use of Surfactant washes

Surfactant washes should be pumped prior tocementing job in turbulent flow regime so that mud cake can be removed as well as all the surfaces can be made water wet. High flow rates should be used so that cleaning action of these fluids becomes more pronounced.

4.9 Optimized composition of spacer

Selection of proper spacer composition can significantly affects the quality of cement job. Sufficient amount of viscosifying agents along with dispersants and weighting material should be mixed so that properties of spacer are easier to achieve laminar flow during its pumping. The analysis of cement quality in offset wells can help to identify poor mud removal zones and its reason. This willhelp in selecting several other parameters especially the volume of spacer and washes.

4.10Dynamic Casing Cementation

Poor cement quality behind the casing leads to the wastage of precious rig time as remedial jobs have to be done to compensate primary cementing. An enormous amount of rig time can be saved by switching from conventional static casing cementing to dynamic casing cementing because dynamic cementing leads to better zonal isolation and excellent cement quality. It can achieve these benefits as it allows casing movement right from the start of cementing operation which results in mobilization of static mud pockets and breaking of gels that cannot be properly achieved through other techniques.

With dynamic cementation, standoff has a time element associated with it which keeps on changing its profile in the well. It introduces a beneficial effect which is hydraulic in nature and cause fluctuation in pressures that can aid in breaking the gels and enable the slurry to mobilize static mud.

4.11Targeting optimized Standoff Profile

Earlier chapter highlights the importance of casing centralizations and its impact on the efficiency of primary cementing job. Proper centralization of casing can save time that would be spent during remedial jobs in order to fix the shortcomings of primary cement operation.

Optimization of centralizer should be done by both operators and vendors based on their field experience as well as commercially available software as the equations and theory of casing deflection in the presence of centralizer are well set up. Type of centralizers along with its characteristics should be in line with wellbore behavior and properties. Software technology should be used to avoid impractical hand calculation for standoff profile by conducting sensitivity analysis for spacing and placement. Proper standoff level should be maintained during optimization process by keeping convenient rig site installation of centralizers in mind.

4.12 Water-to-Cement Ratio

One of the application areas of remedial cementing is to fix leakage of gas/water from annulus due to uncemented casing part located at top sections of wells. The reason behind casing being uncemented is the presence of free water which has not been used by cement during its hydration. Therefore, proper amount of water in cement is very critical to avoid such situations. Water-to-Cement Ratio (WCR) is quantity that should be optimized with the focus on ease in slurry pumping, sufficient compressive strength development, better slurry yield and negligible amount of free water after hydration.

4.13 Use of inorganic salt brines as basefluid

Setting time of cement depends on quality of water being used in the mixing process of cement. Different types of water are available that can be used as base fluid to mix cement additives. Water having inorganic salts dissolved in it, like sea water, proves to accelerate the setting process of cement without reducing its pumpability. Therefore, base fluid composition should be designed and resulting slurry should be tested in consistometer to check its setting time.

4.14 Cement density

Losses during cementing operation are not uncommon especially when the heavy cement slurry is used. Likewise, flow in well occur if the density of cement is maintained at lower level than that of pore pressure gradient. Both scenarios have a tendency to prolong the cementing operation which leads to high cost and excessive time. Therefore, special care should be taken while selecting density that can meet the requirement of well. Table 9 can be used as screening criteria for type of slurry which directly affects slurry density.

Table 9 Cement Slurry Type with corresponding Density Range [27]

TYPE OF CEMENT SLURRY	SLURRY DENSITY RANGE (LB/GAL)
Neat Slurry	14-18
Densified and Weighted	16-22
High Water Ratio Slurry	11-15
Extended Slurry with Glass Bubbles	7.5-12+
Extended Slurry with Ceramics Beads	9.5-12+
Foam Cement	6-12+

4.15 Some additives to help overcome gas channeling

Adding 2.5-6% by weight of anchorage clay to the cement at a temperature of 93.5° Celsius to overcome the shrinkage problem and the void resulted by that which leads to gas migration. Adding 4-8% by weight of a class of synthetic rubber powder eliminates the migration of gas through the cement itself, it seals the microvoids occurring within the cement during setting. Ironate sponge has also shown good results according to the same research, ironate sponge addition to the slurry delivers better bond to the casing due to higher magnetic field of ironate sponge under higher temperatures of deeper formation [23].

4.16Leaving the tubing in the hole under Plug and Abandonment

Pulling out all the production tubing before placing the cement plug is the most challenging and expensive phase during plug and abandonment,this requires a rig which has a daily renting fee of several millions NOK and consumes much time. In addition, the tubing is normally not reused because of the damage and corrosion it got previously.
As a solution to this case, leaving the tubing in the hole would save much time and cost of the renting the rig and instead using light vessels. We should keep in mind that oil companies in Norway get to write-off 78% of the plugging costs from the taxes they pay, so reducing the plugging cost will be beneficial to the whole society. In 2016, Aarbakke innovation announced that they have developed a tool which is run down the well and which eliminates the need of pulling out the production tubing and still sealing the well properly.

While Aarbakke Innovation suggests a tool to seal off the well with the production tubing left in the hole, DrillWell Research Centre conducted in march 2016 a research and confirmed that just placing a cement plug in the well as it is, without running down any special tools using expandable cement would give good enough seal to the well during permanent plug and abandonment, they even conducted a test where they attached control lines to the tubing and that did not affect the result at all. Neither did the poor centralization of the tubing affect the quality of the plugging.

5 CONCLUSION

Proper primary cementing is the key to drilling and completion success, however, there are several factors and details that many engineers may not be aware of that can lead to failure of the cement job that necessitates a remedial cement job which will cost the company big amounts of money. Type of cement used, method of cementing in the different circumstances are crucial to a successful cement procedure. Hole conditioning, pumping procedure, centralization of the casing, moving the pipe, using of preflushes are among the processes that cementing engineer should be very aware of to avoid any failure.

Many companies follow the API recommendation of 500 psi compressive strength and 8 hours of waiting time before drilling of the next section. API also suggests a minimum of 250 psi compressive strength. Researches show that 500 psi and 8 hours are actually to much and 250 psi with 4-6 hours waiting before drilling the next section would be sufficient in most cases. This saves much of the costly time. 500 psi and 8 hours is more necessary for colder environments since temperature plays an important role in setting time. One should consider longer setting time on surface casing cementing than on the deep.

New technologies and procedures allow to plug the well permanently and in a safe manner without pulling out several kilometers of production pipe, this eliminates the need of renting expensive rigs to pull out the production pipe and instead use light vessels.

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