

# Chapter 7

## Fundamentals of Plug Placement



The best practice of permanent plug and abandonment requires a cross sectional barrier, which is known as *rock-to-rock barrier*. The barrier is placed at the right depth where formation is capable to hold the maximum anticipated pressure. To fulfill the requirement, two general situations could be encountered: openhole plug placement or cased hole plug placement.

### 7.1 Openhole Plug Placement

To place a permanent cement plug in an openhole, the fluid in the well needs to be replaced with cement. As the compositions and properties of drilling (or milling) fluids and cement slurries vary widely, severe contamination can occur at the interface of drilling fluid and cement slurries due to incompatibility. Therefore, fluid removal during cement plug placement is a crucial task.

#### 7.1.1 Fluid Removal

Fluid removal has been an interest for cement engineers for many years. To achieve the objectives, drilling fluid and pre-flushes must be fully removed from the openhole interval and be exchanged fully with cement or any plugging material. The fluid removal process is a function of borehole quality, circulation and displacement efficiency, fluid conditioning and properties of drilling fluids, spacers and washes [1–6]. Fluid removal process can be carried out in two main different ways: hydraulically or mechanically. In the hydraulic process, spacer fluids with specific viscous behavior are pumped ahead of cement slurry to displace drilling or milling fluid. The contamination effect of these spacer fluids on cement is less compared to drilling or milling fluids.

One major difference, when considering milling operation during permanent P&A, is that a window of casing is milled to reach the formation and therefore, milling fluid is used instead of drilling fluid. So, compatibility of cement and milling fluid is strongly dependent on the chemistry and properties of milling fluid; therefore, milling fluids will be reviewed briefly.

### 7.1.2 Milling Fluid

When casing is milled away, the generated debris known as *swarf* (Fig. 7.1) needs to be transported to surface or left behind in the bottom of the well as will be discussed in Chap. 8. As drilling fluids do not have the transportation capacity of swarf, special fluids known as milling fluids are used. Milling fluids are usually water based. Of milling fluids one can list: bentonite/bicarbonate mud, bentonite/MMH (Mixed Metal Hydroxide) mud, xanthan gum/sea water mud, and potassium formate milling fluid [7–9]. Considering the geometry of the circulation system and non-Newtonian behavior of milling fluids, the hydrodynamics of swarf transportation and hole cleaning are identical to cutting transportation and hole cleaning during drilling. However, given the fact that swarf are much larger (see Fig. 7.1), having higher density compared to rocks and having irregular shapes, the problems are different [7]. A desired milling fluid should have high transportation capacity with low shear rate viscosity.

When considering the transportation of swarf by milling fluid, settling velocity of swarf in static and dynamic fluids and transportation velocity of debris are important. Experimental studies show that in static fluids the gel strength and effective viscosity of milling fluid are critical factors besides, the shape, surface area and the settlement orientation of swarf. The gel strength causes suspension of swarf but when the swarf is sharp, the gel strength can be overcome.



Fig. 7.1 Swarf from a milling operation in the North Sea (Courtesy of equinor)

When swarf is in dynamic conditions, flowing fluid, the mean circulating velocity required to prevent the swarf from settling is significantly higher. In dynamic conditions, there are areas close to the wall where the flow velocity is near zero and large volumes of swarf will be located in an un-sheared zone [7].

### 7.1.3 Hydraulic Mud Removal

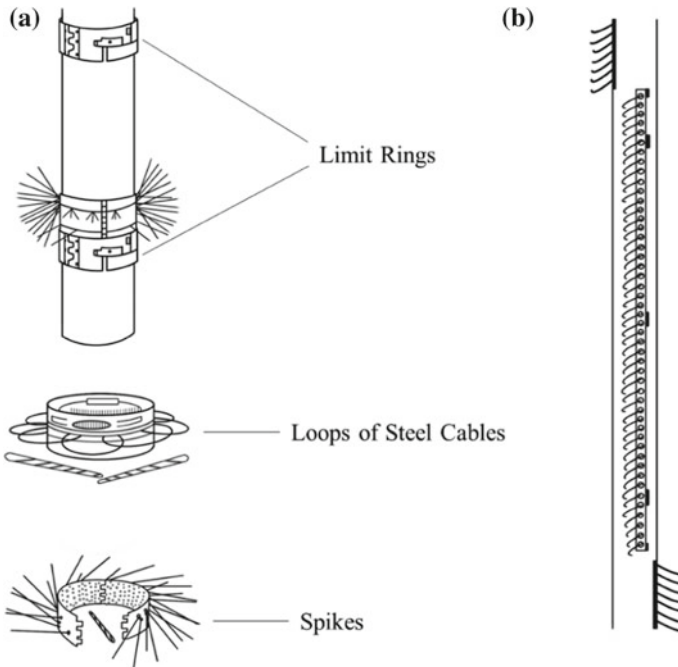
*Spacer* or *displacement fluids* are type of fluids which minimize the cement contamination and improve the fluid removal efficiency. Any liquid which physically separates a special liquid from another is known as spacer fluid. In most practical operations, a cement slurry should have turbulent flow conditions to displace drilling fluid. But the flow regime cannot be achieved because of operational restrictions. So, spacer fluid needs to be selected to reach a turbulent or pseudo-laminar flow to remove the left fluids. Displacement fluid is usually used to force a cement slurry out of the workstring or into the annulus behind casing.

A spacer should have the following characteristics: compatible with a given type of drilling fluid or milling fluid, including bentonite muds and polymer based muds. The spacer properties should not affect the cement slurry viscosity nor changing the pumping time; to tolerate high solids and mud cake; to tolerate addition of wetting agents, dispersants, friction reducers, and retarders; low-fluid-loss properties; and permitting turbulence flow regime at low pumping rates for efficient mud removal [10–14]. Although spacers are used to remove drilling fluid and mud cake but it is unlikely to remove the mud cake without using mechanical aids.

### 7.1.4 Mechanical Filter Cake Removal

To clean the formation interface for achieving better bonding between the plugging material and formation, mechanical devices known as *wall cleaners* can be utilized. *Mud cleaners* or *scratchers* (sometimes called *mud stirrers*) are mechanical devices used to remove the mud or condition the drilling fluid filter cakes off of openhole wall for achievement of a better shear bond strength and hydraulic bond strength. The wall cleaning operation is different from *reaming* and *under-reaming*. *Reaming* operation is for enlarging wellbore by utilization of a mechanical device. However, enlarging hole is avoided during plug placement as it creates challenges during cement placement. Mechanical cleaners are fastened on the outside of workstring to agitate the mud and make it easier to displace it. The introduced motion breaks the gel strength of the mud filtercake and with help of wash fluid, the drilling fluid is displaced easier. The *rotational type* and the *reciprocation type* scratchers are the two commonly used types, see Fig. 7.2.

The rotational type scratcher cleans the formation when workstring is rotated. A continuous length of scratcher is fastened on the workstring, Fig. 7.2a. The steel spike



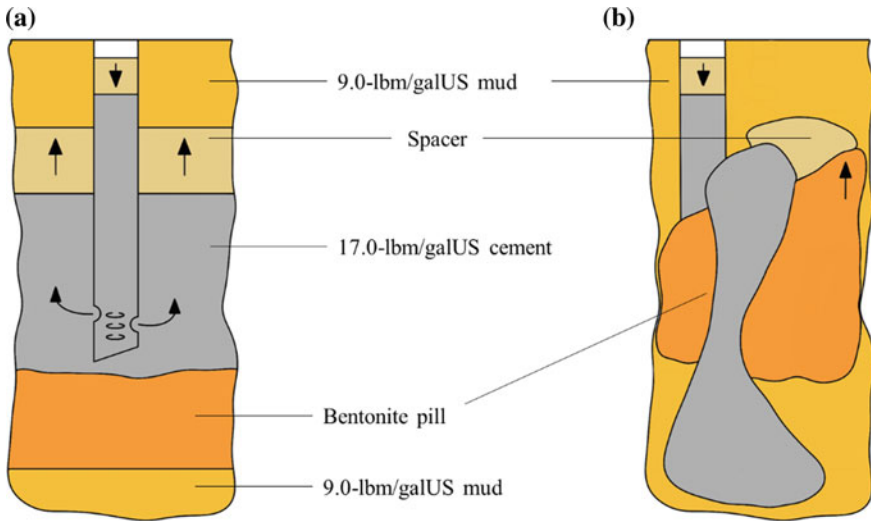
**Fig. 7.2** Two commonly used scratchers: **a** rotational type scratcher, **b** reciprocation type scratcher

or steel cable sets are installed on workstring with different phasing to improve the cleaning efficiency.

The reciprocation type scratcher cleans the formation has either steel spikes or steel cables. Depending on the length of zone to be cleaned, one or more scratchers are attached to outside of workstring. Each scratcher is limited by two rings or clamps in the desired interval: one above and one below, Fig. 7.2b. These types of scratchers clean the formation when workstring is moved upwards and downwards.

During the mechanical cleaning operation, a wash fluid is pumped to displace and wash the mud and filter cakes. If the plug is off-bottom plug, when the interval is clean, a viscous reactive pill is pumped to create a base for cement plug and keeping plug in position, Fig. 7.3. *Viscous reactive pill* is a special blend of drilling fluid containing silicate component, which has higher density than cement slurry. When the calcium in the cement reacts with the reactive pill, a gel forms that prevents flow between cement and the pill. The reactive viscous pill is compatible with cement slurry and its high yield stress provides base functionality while cement sets. When the reactive viscous pill is in place, the cement slurry is placed on top of it which is across the cleaned formation.

If the drilling fluid present in bore is an oil-base mud, a viscous spacer is necessary before and after pill to minimize slurry contamination. The failure roots of plugs in openholes have been investigated by different authors and include the following [16]:



**Fig. 7.3** Cement plug is placed in an openhole on a viscous pill, **a** ideal cement set, **b** unsatisfactory results for a cement plug placed on a lighter fluid (Taken from well cementing) [15]

- Poor mud removal
- Poorly designed slurry properties
- Incorrect estimation of slurry volume
- Poor downhole temperature estimation
- Poor job execution and placement
- Instability of the interfaces and swapping.

When cement plug is placed, it is left undisturbed until it develops high enough strength. When cement plug solidified sufficiently, top of cement is *dressed off* (top of cement is drilled out until hard cement is reached). As the plug is in an openhole, pressure testing is meaningless. Therefore, the TOC is tagged and a certain weight is applied on cement. If position of cement did not change, the cement plug is regarded as qualified. However, if the plug is not capable to hold the weight or the tagged TOC is not at the right depth, the plug is regarded as disqualified and a new cement plug needs to be established. In case of wireline and coiled tubing utilization, the maximum weight availability is limited compared to use of drillpipe.

## 7.2 Cased Hole Plug Placement

When considering plug placement for a cased hole, two different scenarios can be considered: either qualified annular barrier is proven or annular barrier is disqualified. Each case can dictate different operations.

### **7.2.1 *Qualified Annular Barrier***

If the annular barrier behind casing is qualified, then a mechanical plug is installed to create a foundation for cement plug. The mechanical foundation is not a part of permanent well barrier envelope but has the following advantages: avoiding gas invasion of cement while it sets, avoiding dispositioning of cement while it sets, and minimizing the cement contamination. When the mechanical plug is installed, it is pressure tested. If it successfully passes the pressure test, then cement plug is poured on top of it and left undisturbed until it develops high enough strength. When cement is solidified, cement is dressed off and tagged. As the mechanical plug has already passed the pressure test, the pressure testing of the cement plug is meaningless. However, if mechanical plug has not tested or did not successfully pass the pressure test, the cement plug is pressure tested and documented. Pressure test failure of cement plug means that another cement plug needs to be established. Different authorities require different plug length and different rate of pressure test.

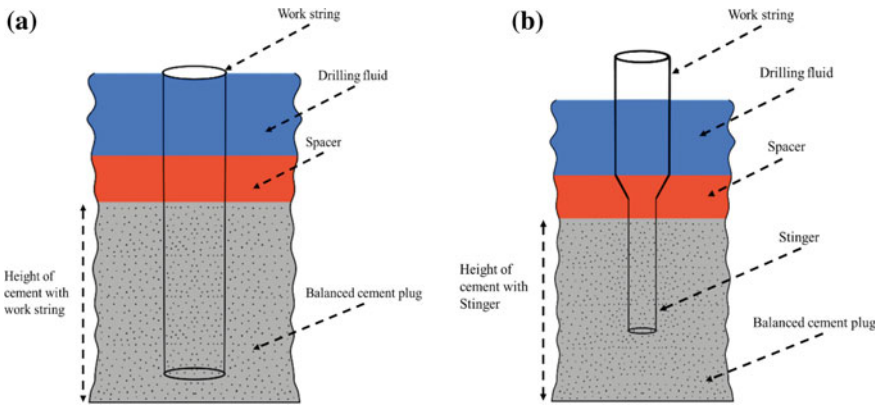
### **7.2.2 *Disqualified Annular Barrier***

Wherever the quality of casing cement is not qualified or there is no annular cement, access to the annular space behind casing should be established to place a qualified barrier both inside and outside the casing. The conventional approach is section milling. The operation of removing a part of casing by milling or machining the casing is called *section milling*. To mill out casing steel, special knives are employed. Section milling is explained in Chap. 8. New methods exist called Perforate, Wash and Cement (PWC). PWC is described in the next chapter.

## **7.3 Plug Placement Techniques**

### **7.3.1 *Balanced-Plug Method***

This is the most common plug placement technique used for placing permanent plugs. A work string is run into the hole to the desired depth for the plug base. As the work string is surrounded by mud, spacer and chemical wash are pumped ahead and behind the slurry to avoid mud contamination and ensure wetting of the surface of casing or formation. Cement slurry is pumped down through the work string and up in the annulus between the work string and casing or formation. The volumes of spacer ahead and behind the slurry are calculated so that the spacer height inside and outside the work string end up at the same level, Fig. 7.4.



**Fig. 7.4** Balanced-plug placement technique, **a** common work string, **b** deploying a stinger to minimize the agitation of slurry during pulling out of slurry

**Example 7.1** You are asked to install a balanced plug across a suitable formation whereby the plug base is supposed to be at 10,000 ft measured depth. For this job, a 4½-in. drillpipe will be used as a workstring in an openhole with 8¾-in. diameter. The plug length is expected to be 200 ft and 24 bbl of fresh water will be pumped ahead of cement as spacer. Additional information: string capacity = 0.01422 bbl/ft, annular capacity = 0.0547 bbl/ft. Assume the wellbore is vertical.

- (a) Calculate the required volume of cement.
- (b) Calculate the height of cement plug with workstring in.
- (c) Calculate the required volume of spacer behind slurry.
- (d) Calculate the volume of displacement fluid.

**Solution** The goal of balanced plug placement technique is to have an equal drillpipe pressure and annular pressure, at the plug base (see Fig. 7.5). It can be written as:

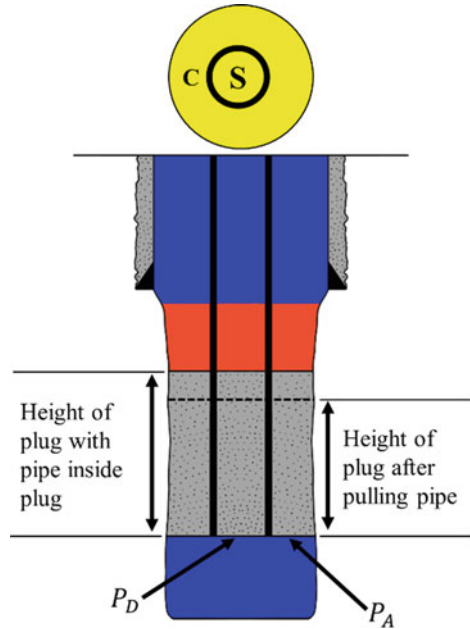
$$\begin{aligned} \Delta P_{CD} + \Delta P_{WD} + \Delta P_{MD} &= \Delta P_{CA} + \Delta P_{WA} + \Delta P_{MA} \\ PD &= PA \end{aligned} \tag{7.1}$$

whereas  $\Delta P_{CD}$  is the hydrostatic pressure exerted by cement inside workstring,  $\Delta P_{WD}$  is the hydrostatic pressure exerted by spacer inside workstring,  $\Delta P_{MD}$  is the hydrostatic pressure exerted by mud inside workstring,  $\Delta P_{CA}$  is the hydrostatic pressure exerted by annular cement,  $\Delta P_{MA}$  is the hydrostatic pressure exerted by annular spacer, and  $\Delta P_{WA}$  is the hydrostatic pressure exerted by annular mud.

In this example, the spacer ahead and behind the slurry are the same type with the same characteristics. However, there are circumstances where spacer ahead and behind the slurry are different. The latter case is given as problem, at the end of this chapter.

- (a) Volume of cement assuming no washout:

**Fig. 7.5** A balanced plug whereas the spacer inside and outside workstring are in the same level and the same chemistry



$$V = \frac{\pi D^2}{4} * h \tag{7.2}$$

where  $D$  is wellbore diameter (ft), and  $h$  is plug length with no workstring inside plug.

$$V = \frac{\pi \times 8.75^2}{4} \times 200 \times \frac{(1 \text{ ft})^2}{(12 \text{ in.})^2} = 83.517 \text{ (ft}^3\text{)}$$

(b) Height of cement plug when workstring is inside plug is given by equation [15]:

$$H = \frac{V}{C + S} \tag{7.3}$$

where  $C$  is annular capacity (bbl/ft),  $S$  is workstring capacity (bbl/ft),  $V$  is volume of slurry (bbl), and  $H$  is height of plug with pipe in place (ft).

$$H = \frac{83.517 \text{ (ft}^3\text{)} \times \frac{1 \text{ bbl}}{5.615 \text{ ft}^3}}{(0.01422 + 0.0547) \frac{\text{bbl}}{\text{ft}}} = 215.814 \text{ ft}$$

(c) The required volume of spacer behind slurry is supposed to be at the same height as spacer ahead of slurry. It means:



$$L_{sp2} = L_{sp1} \quad (7.4)$$

Then, it can be written as:

$$\frac{V_{sp2}}{S} = \frac{V_{sp1}}{C} \quad (7.5)$$

where  $V_{sp1}$  is the spacer volume ahead of slurry (bbl) and  $V_{sp2}$  is the spacer volume behind slurry (bbl).

$$\frac{V_{sp2}}{0.01422} = \frac{24}{0.0547}$$

$$V_{sp2} = 6.24 \text{ (bbl)}$$

- (d) Volume of displacement fluid is the amount of fluid which needs to be pumped behind spacer to level the heights and keep the pressure equal, at the base of plug. The displacement volume in bbl is given by Eq. (7.6):

$$V_{dis} = S \times [L_{dis} - (H + L_{sp2})] \quad (7.6)$$

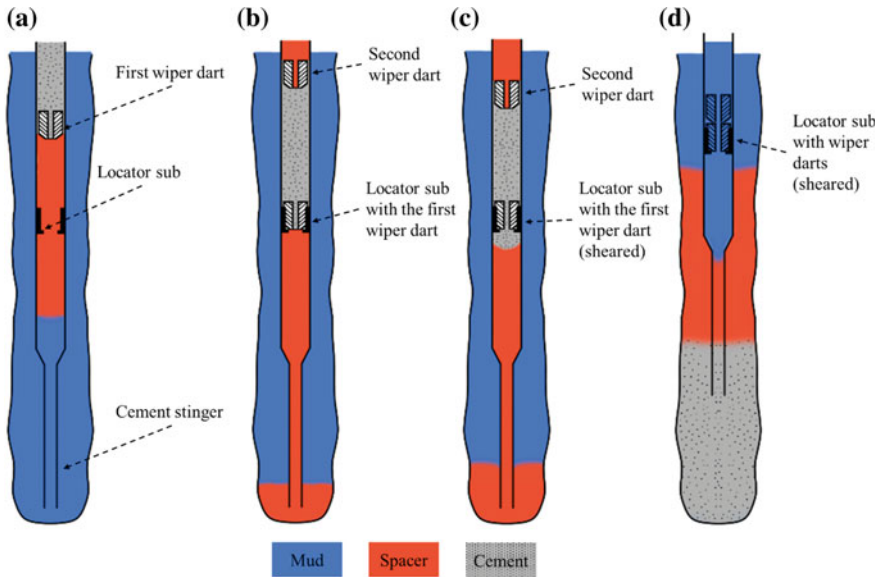
whereas  $L_{dis}$  is length to be displaced which is measured depth (ft), and  $L_{sp2}$  is length of spacer behind slurry.

$$V_{dis} = 0.01422 \times [10,000 - (215.814 + 438.7)] = 132.89 \text{ bbl}$$

Cement plug contamination is one of the main challenges associated with the balanced plugs and can occur in three different ways: mud contamination during pumping, contamination caused by cement agitation while pulling the work string out of the plug, and plug displacement while it sets. Contamination during pumping the slurry may occur in the slurry-spacer interface and due to poor mud removal from formation or casing surface. The best practice to minimize the effect is to properly design the type, volume and flowrate of spacer and chemical wash or use a two-plug method.

### 7.3.2 Two-Plug Method

To minimize the contamination of the cement plug with the fluid ahead and behind, the two-plug method is used (see Fig. 7.6). In this technique, a wiper dart is run ahead of the cement plug (between the lead cement slurry and spacer) and another wiper dart behind the slurry (between the tail cement slurry and spacer). Thus, from surface down to a depth close to the tailpipe or stinger, the slurry is fully separated from the spacer and consequently, the risk of contamination is decreased. Each wiper dart has a diaphragm which holds pressure up to a certain point and ruptures at a



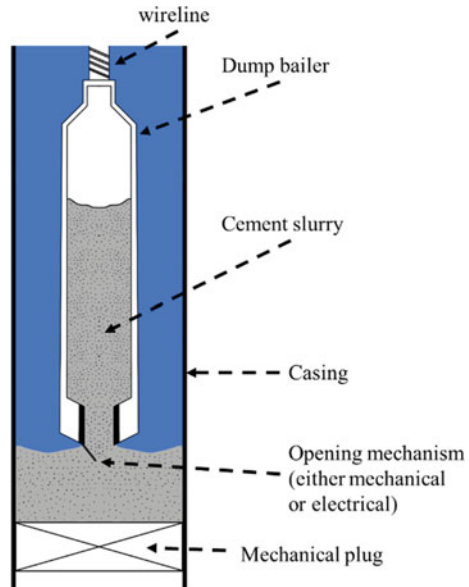
**Fig. 7.6** Two-plug method; **a** first wiper dart separates cement from spacer until it lands on the locator sub, **b** second wiper dart separates cement from spacer behind cement, **c** the diaphragm of the first wiper dart is sheared due to the increased pressure and cement slurry passes through it, **d** second wiper dart seats on the first wiper dart and its diaphragm is sheared due to the increased pressure and the spacer passes through it [15]

higher pressure. The work string is equipped with a locator sub close to the stinger or tailpipe. When the first wiper dart seats on the locator sub, the pressure increases until the diaphragm ruptures, and the cement passes through the first wiper dart. Afterwards, the second wiper dart seats on the first wiper dart and causes a pressure increase. Due to the increased pressure, its diaphragm is ruptured and spacer passes through.

### 7.3.3 Dump Bailer Method

It is a wireline tool for placing small volumes of slurries at the desired depth with a minimal contamination. It is normally used only for onshore wells. The bailer is filled with cement and run into the wellbore. When it reaches the desired depth, the bailer cap is opened electronically via a signal or mechanically via touching a mechanical foundation. It is a common practice to use a mechanical foundation when a dump bailer is going to be used, Fig. 7.7. Some of its advantages are: minimizing the effect of contamination, it is inexpensive, drilling rig is not necessary for the operation, plug depth is easily controlled and operational time is significantly less compared to other methods. Low capacity of bailers and multi runs may be necessary, cement

**Fig. 7.7** Dump bailer method for plug placement



may set inside the bailer due to static conditions inside the bailer while running it down to the desired depth, and uncertainties associated with mud or spacer removal are some of the limitations for this method. It should be noted that slurry gelation or instability must be avoided to ensure that the slurry can exit the dump bailer.

### 7.3.4 Coiled Tubing Method

Coiled tubing is a long continuous pipe wound on a spool. The pipe is straightened prior to being pushed into the wellbore and rewound to recoil the pipe back onto the transport and storage spool. Depending on the pipe diameter and the spool size, coiled tubing can range from 2000 to 15,000 ft or greater lengths. Table 7.1 presents typical coiled tubing sizes.

Utilization of coiled tubing for remedial cementing began in the early 80's. Since then, the technique has received considerable attention. This technique has proved to be very economical to place small volumes of cement slurries required in curing channeling behind tubulars, blocking off perforations, squeezing cement into perforations, curing lost circulation zones during drilling, and placing cement whipstocks [17]. As the pipe is continuous, challenges associated with making connections and the need for a conventional rig are minimized which means it is a cost effective technique. However, there are some concerns limiting the use of coiled tubing for cement plug placement including fatigue problems, hole cleaning, special cement slurry design, unit space and capacity, crane capacity, and local regulations.

**Table 7.1** Industry coiled tubing sizes available to date for material grades GT-80 (courtesy of global-tubing)

Specified dimensions		Axial load capacity			Pressure capacity		Torsional strength		External displacement	Internal capacity per 1000 ft	
Outside diameter (in.)	Wall thickness (in.)	Inside diameter d (in.)	Nominal weight (lb/ft)	Yield load (lb) $t_{nom}$	Tensile load (lb) $t_{nom}$	Yield pressure (psi)	Hydrotest pressure 90% (psi)	Yield (ft/lb) $t_{min}$	Ultimate (ft/lb) $t_{min}$	Barrels	Barrels
1.250	0.190	0.870	2.16	50,620	55,680	23,040	15,000	1,097	1,206	1.52	0.74
1.500	0.087	1.326	1.32	30,900	33,990	8,850	7,970	955	1,051	2.19	1.71
1.750	0.109	1.532	1.91	44,950	49,950	9,510	8,560	1,609	1,770	2.97	2.28
2.000	0.109	1.782	2.21	51,800	56,980	8,320	7,490	2,149	2,364	3.89	3.08
2.375	0.125	2.125	3.01	70,690	77,750	7,950	7,160	3,463	3,809	5.48	4.39
2.625	0.134	2.357	3.57	83,890	92,280	7,740	6,970	4,571	5,028	6.69	5.40
2.875	0.156	2.563	4.54	106,600	117,260	8,240	7,420	6,330	6,963	8.03	6.38
3.250	0.156	2.938	5.17	121,310	133,440	7,290	6,560	8,236	9,060	10.26	8.39
3.500	0.175	3.150	6.23	146,240	160,870	7,630	6,870	10,708	11,778	11.90	9.64
4.500	0.224	4.052	10.25	240,730	264,800	7,610	6,850	22,639	24,962	19.67	15.95
5.000	0.276	4.448	13.96	327,690	360,460	8,510	7,660	34,231	37,654	24.29	19.22

*Fatigue problems*—Coiled tubing fatigue life is a major area of concern as the coiled tubing diameter increases for cementing applications. Each time that coiled tubing is spooled on and off the reel and over the gooseneck of the coiled tubing unit, it is stressed. This concern is greater in coiled tubing with larger diameters. Another cause is the internal pressure in the coiled tubing during bending and straightening [18]. As there is no practical non-destructive means of measuring the amount of damage accumulation, coiled tubing lifetime prediction models have been developed to predict the coiled tubing properties.

*Hole cleaning*—Limited flow capacity due to the size of the coiled tubing and lack of mechanical agitation effects through pipe rotation reduces the hole cleaning efficiency in large hole sizes [19].

*Unit space and capacity*—When considering the feasibility of coiled tubing for cementing, the unit deck area for placing the coiled tubing equipment such as reel, injector, pumping equipment, cementing equipment, and testing equipment need to be studied. In addition, the unit structure should have the capacity to hold the weight of equipment without introducing a risk of failure. For onshore wells the soil and the area should be able to hold the weight and also for offshore wells platform, drillship, vessel, semi-submersible or other working units the weight must be considered. As cementing utilizing a coiled tubing unit requires larger pipe diameters, the size and capacity of pipe handling equipment (e.g. injector heads, reels, well control equipment, etc.) have to be increased. Therefore, the unit space and capacity need particular consideration.

*Crane capacity*—In case of offshore activities, platform cranes must be able to lift up equipment from a supply boat to platform or any other offshore working unit [20]. The increase in weight and dimensions created by larger pipe diameters require higher crane capacity and introduces additional hazards.

*Local regulations*—Regulations aim for performing a safe coiled tubing operation which requires quality control of coiled tubing, wellsite safety standards, and safe deployment of tools in and out of the well. Well control equipment (e.g. BOPs), pressure rating of coiled tubing, fatigue prediction, unit capacity, and crane capacity are some of the main concerns focused on by local regulators. However, different regulatory authorities have different criteria.

*Cement slurry design*—As coiled tubing has a lower flow capacity compared to drillpipe, a standard coiled tubing cement recipe is not the same as a standard primary cement recipe. Due to the mixing energy introduced by coiled tubing on the cement slurry, a mechanical acceleration result. Therefore, a typical cement slurry designed for placement with coiled tubing has a longer thickening time, and lower viscosity and yield stress [21].

## 7.4 Mud Displacement During Cementing

The replacement of drilling fluids with cement to establish a barrier and to seal formation pressures hydraulically is the main task to be achieved during plug placement, besides the prime physical properties of the cured cement. Several parameters influencing mud displacement efficiency during plug placement include: hole geometry and inclination, flow rate, degree of turbulence, ECD, cement or mud and spacer design, hole conditioning, rheological behavior, buoyancy and plug stability, pulling out of plug, size of work string, and centralization of work string [3, 22–26]. Obviously, no single technique, will magically make mud displacement and cementing a success.

*Hole geometry and inclination*—The geometry of openhole where the cement plug is to be placed is very important for mud displacement and pumping of the correct volume of cement. When the milled section (openhole) has a constant diameter, it is referred to as in-gauge. An *in-gauge hole* has a round cross section but as the cross section starts to deviate from the round shape, it is referred to as an oval hole, Fig. 7.8. If the milled section has variations in diameter, it is called an *irregular wellbore geometry*, and has resulted from washouts.

When washouts exist, the annular flow velocity is less than for in-gauge portions of the hole. If the annular velocity is low enough, the mud will be left in the washout in a gelled state and the mud removal by cement becomes very difficult. Another challenge introduced by washouts is that if there is a large uncertainty in hole size, the cement volume will be underestimated and the plug length will be less than required. Therefore, the hole is usually callipered to better describe the wellbore geometry.

In deviated holes, unstable fluid interfaces with regards to gravitational forces, and fluid contamination introduce complications to balance the fluids during plug placement. A properly designed plug can be contaminated during pulling the tailpipe of the work string out of the cement plug, especially in deviated sections [27]. In addition, deviated boreholes intensify challenges related to free fluid and particle segregation [28].

*Flow rate*—Another major parameter which affects the displacement process is the flow rate. As drilling fluids and cement slurries are non-Newtonian fluids, they

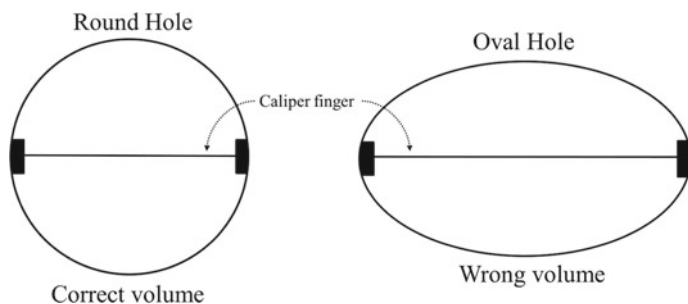
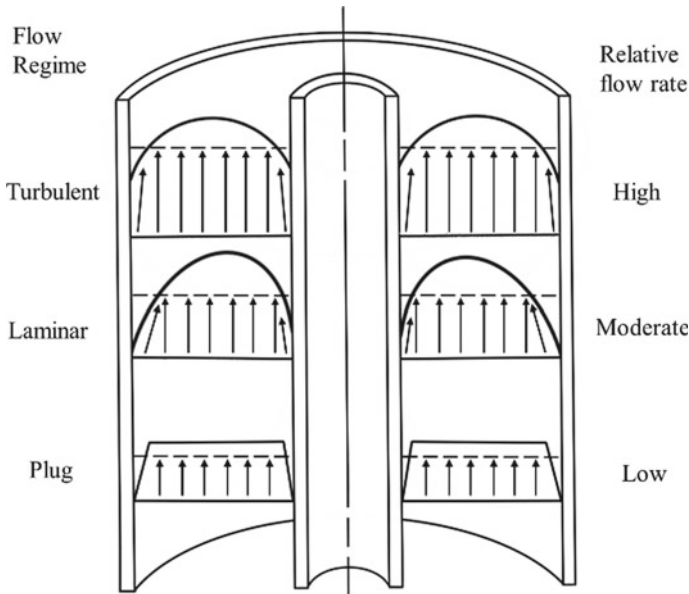


Fig. 7.8 Caliper log may not be able to read the oval-hole diameter



**Fig. 7.9** Different flow regimes in which a non-Newtonian may exist (balanced-plug placement technique)

require a certain pressure drop to establish a significant flowrate. There are two possible flow regimes that a non-Newtonian fluid may have (see Fig. 7.9); laminar flow and turbulent flow. Sometimes plug flow regime is also defined as another flow regime but it is a pattern of laminar flow. As shown in Fig. 7.9, the bulk annular velocity profile (dashed lines) and the actual velocity profile (solid lines) are not equal, and the axial velocity (arrows) in the laminar flow regime is not as uniform across the annulus as in the turbulent flow regime. Axial velocity distribution is a maximum in the center of each flow regime and higher than the axial velocity of fluid adjacent to the boundaries [29]. Therefore, mud removal from boundaries might be complex and ineffective.

Cement contamination by drilling fluid is more prone when the drilling fluid removal is inefficient. Haut and Crook [29] showed that the contamination is due to instabilities occurring at the cement-mud interface where the velocities are not strictly axial. The formation of instabilities are a result of nonlinear coupling of changes in shear rate and shear stress at the interface of the fluids, and lead to mud channeling.

*Degree of turbulence*—In order to achieve a turbulent flow regime for cement, a high flow rate is required; however, it may be unachievable if the slurry has a high viscosity. When a shear force is applied on a non-Newtonian fluid, the fluid resists to flow and undergoes an elastic deformation until the elastic structure breaks down (yields) at some point and the material begins to flow [30]. In practice, turbulent flow of cement during plug placement is less likely to be achieved because of operational

limitations. Nevertheless, from a practical point of view, it is important that the frictional pressure drop of cement to be higher than the frictional pressure drop of drilling fluid.

*Equivalent circulating density*—Long-term zonal isolation requires effective mud displacement which requires the use of high pumping rates during cementing. However, when considering a depleted formation or a subsided field, the formation fracture pressure is lower than the original formation fracture pressure and consequently a narrow pressure window should be expected and tight ECD management is a priority. Therefore, pumping rates during cementing operations are limited. High flowrate results in high frictional pressure, which may exceed the fracture pressure of the formation. This scenario gets even more complex in depleted long horizontal wells. Modifying the rheological behavior of cement and optimizing the pumping rates are to be considered for maintaining low ECDs and to help ensure effective cementing operations [31].

*Cement/mud and spacer design*—There are several types of spacer systems available including: flushes, gels, water based, oil based, and emulsions (water in oil emulsion and oil in water emulsion). Among these, flushes are mainly used to achieve turbulent flow for improved mud removal [32]. Spacers are designed to improve cement bonds by water-wetting the cement-pipe or cement-formation interfaces while not destabilizing any sensitive zones and not adversely affecting the mud or cement properties [33]. In order to obtain an improved mud removal, studies show that density of displacing fluid should be at least 10% heavier than the displaced fluid, and the friction pressure of the displacing fluid should be greater by at least 20% than the displaced fluid [13]. The maximum mud removal occurs when the viscosity profile of spacer systems is higher than the viscosity profile of the drilling fluid and lower than the cement slurry.

The analysis of removing drilling fluid and replacing it with cement can be performed properly by simulating multiphase flow. In a multiphase flow simulation, interfaces between cement and space fluid, and spacer fluid and drilling mud are presented by solutions of the governing equations [2, 34–37].

In order to minimize the poor mud displacement, a cementing checklist is prepared as guideline [24, 38]:

1. Determine the displacement rates for cement plug on the basis of the mixing and pump capabilities, and ECDs during cementing for typical spacer rheology.
2. Select the spacer and check its compatibility with the mud system.
3. Once the spacer has been selected, determine its viscous properties at bottomhole circulating temperature (BHCT) and bottomhole pressure.
4. Recalculate ECDs during cementing by using viscosity to select the mix, pump, and displacement rate.
5. Calculate cement volumes and annular velocities on the basis of a multi-finger caliper log.
6. Condition the drilling fluid to obtain lower viscosity.
7. Keep solids loading down, especially in high-angle holes.

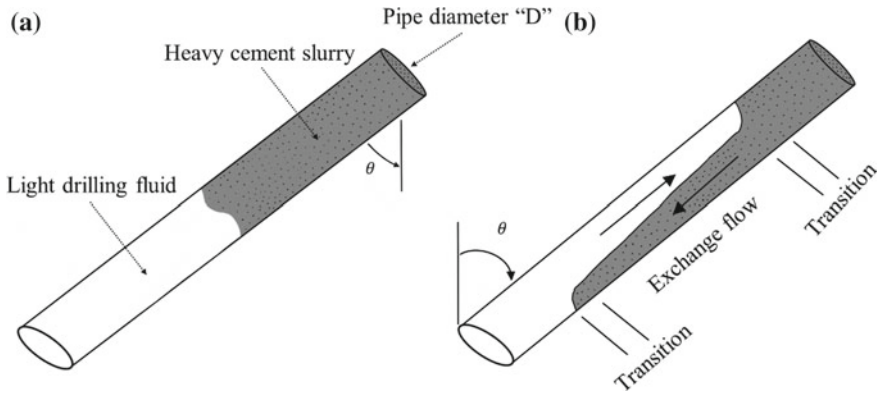


8. Calculate the surge pressures while running the work string, and run at a speed slow enough to minimize the risk of breaking the formation.
9. Once the work string is at the desired depth, start circulation at the calculated flowrate.

*Hole conditioning*—Due to high viscosity and gel strength, drilling fluids are not suitable for cement plug operations. Hence mud and hole are conditioned prior to placing cement plugs in open holes. Proper hole conditioning means to establish a hole free of swarf, cuttings, gels, etc., whereas the hole has a mud in a fully displaceable or circulatable condition. This allows the spacer and cement slurry to effectively displace the mud in the desired hole interval. The circulatable hole condition should be established before the first barrel of cement-mud spacer is pumped down [39]. In addition, hole conditioning results in mud conditioning which reduces the yield point of mud and consequently enables more efficient mud removal during cement placement.

*Rheological behavior*—In order to improve the mud removal efficiency and avoid fracturing formations, modification of cement slurries may be required (role of sophisticated tools and techniques and skilled personnel are inseparable); density changes or rheological behavior modification may be necessary. If pore pressure restrictions do not allow density changes, then modification of slurry rheological behavior is recommended. As an example, rheology of cement slurry can be modified by improving its thixotropic behavior for a better mud displacement [40]. Thixotropy is the characteristic of fluids which have time-dependent shear thinning properties. In other words, when the fluid is in stationary conditions, it forms a gelled structure. But when the fluid is under constant shear rate, the viscosity is decreased over time until it reaches an equilibrium condition. A thixotropic slurry can create a plug flow regime during placement and improve the mud displacement efficiency [41]. However, thixotropic behavior may challenge the plug stability when cement slurry is placed on a pill and while pulling the work string out of the plug.

*Buoyancy forces and plug stability*—When a cement slurry is placed at the required depth on a less dense drilling fluid, it should resist falling down while setting. Studies performed on the physics of buoyancy driven failure modes of cement plugs placed on drilling fluids, show that a minimum yield stress is required to achieve plug stability. The stability of the interface between drilling fluid and cement is governed by well inclination from vertical, fluids yield stress, the density differences between drilling fluid and cement, the gravity force, and hole diameter [42, 43]. The instability occurring at the interface between two fluids with different densities is known as the *Rayleigh-Taylor instability*. When a cement slurry is placed on a fluid with lower density than the cement in an inclined hole, instabilities in the interface between cement and fluid creates three distinct zones (see Fig. 7.10b); transition zone intruding the mud, exchange flow zone, and the transition zone in the base of cement. The movement of fluids which resulted by the instabilities in the interfaces of cement and slurry caused by buoyancy force is termed slumping motion. In the slumping motion of a cement plug, it is assumed that the bulk of the two fluids moves axially at a slow rate, but in the transition zone, a three-dimensional flow exists.



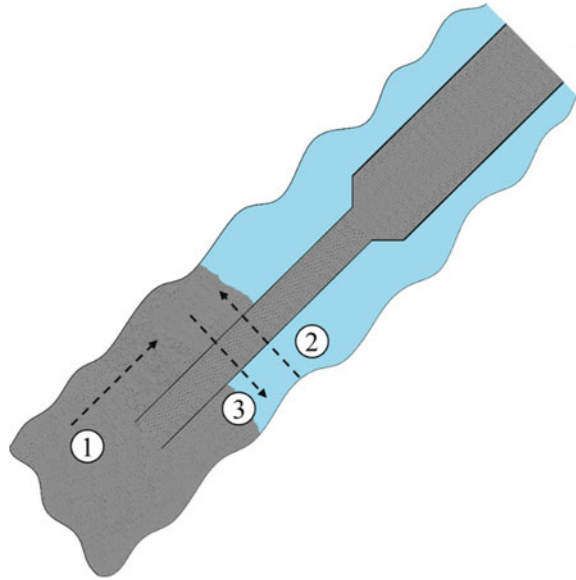
**Fig. 7.10** Schematic of stratified axial exchange flow; **a** cement plug placed on a drilling fluid with lower density than cement, **b** buoyancy force is compromising the plug stability and creates three distinct zones [16]

There are some recommendations to minimize the contamination introduced by buoyancy and to achieve a stable plug, including reducing the density differences between cement and drilling fluid (viscous pill), increasing the yield stress or gel strength of the drilling fluid below the intended cement plug, placing a reactive gelled pill between cement and drilling fluid, and avoiding thixotropic cement slurries for balanced plugs [38, 44, 45]. If the induced agitation passes the YP of slurry, the buoyancy and gravity forces will be activated and the contamination effect will be intensified at the interface between the slurry and the drilling fluid and subsequently, the plug stability. It is believed that during balanced-plug placement when a thixotropic slurry is used, the slurry tends to stay in the end of the tailpipe when the intended cement plug is placed. Pulling the tailpipe out of the static thixotropic slurry creates a drag force on the drilling fluid below the cement, and leads to intrusion of the drilling fluid into the slurry, therefore the slurry is contaminated [45]. However, use of a thixotropic cement slurry, which develops gel strength rapidly, improves the plug stability while cement sets [44].

One solution to minimize the effect of buoyancy forces while cement sets is to install a mechanical foundation and place the slurry on top of it [46]. Then, plug stability is provided while cement sets and the gas invasion is minimized. One limitation for the utilization of mechanical foundations is that they cannot be used in openhole sections.

*Centralization of work string*—An eccentric annulus between work string and formation or casing can channel the displacing fluid to the wide side of the annulus and leave remaining drilling fluid on the narrow side, Fig. 7.11. However, the difference between the density of displacing fluid and displaced fluid creates a hydrostatic pressure imbalance between the narrow side and wide side. On the one hand, the created imbalance pushes the heavier fluid to the narrow side and displacement efficiency is increased. On the other hand, this phenomenon may intensify mud contamination.

**Fig. 7.11** Improper centralization of stinger guides the cement through the large space (1), and gravitational force replaces mud and slurry (2) and (3)



Tehrani et al. [47] studied the effect of eccentricity of pipe on displacement efficiency of mud in inclined wells. Their assumptions included a laminar displacement in the annulus for non-Newtonian fluids in a three-dimensional wellbore. According to their work, good pipe centralization, a high density contrast between drilling fluid and slurry, and positive rheological hierarchy are important factors which improve mud displacement.

Jakobsen et al. [23] considered displacement of fluids with different densities, in eccentric annulus. They concluded that when the displacing fluid is 5% heavier than the fluid to be displaced, the lighter fluid in the narrower part moves to the upper part which is wider. This mechanism, buoyancy-induced, strongly improves the displacement efficiency. This process is recommended when turbulent flow or effective laminar displacement is difficult [48].

*Pulling out of plug*—The assumption behind the balanced-plug calculation method is that the fluid is going to remain in place while the work string is pulled out of plug with minimal falling of the fluid due to the void caused by metal displacement. However, this assumption is correct only when neglecting the role of drag forces between fluids and work string and the volumes attached to the work string surface, and where a mechanical foundation is used as a base. In order to minimize the agitation effect, a tailpipe or stinger<sup>1</sup> with a smaller diameter and wall thickness is deployed. Because of a thinner wall thickness and a smaller diameter, the fluid volumes involved are smaller and consequently contamination is supposed to be minimized [49]. However, Roye and Pickett [50] showed that the initially balanced plug becomes unbalanced as a dynamic condition is imposed when pulling

<sup>1</sup>The stingers are usually made of fiberglass or aluminum pipe.

the work string out of the plug with a pill as a base. When pulling the work string out of hole, a volume of fluid inside the near surface pipe is displaced, as the same volume should be displaced inside the stinger (with a smaller diameter compared to near surface work string pipe), the height of the displaced fluid inside the stinger is higher. Therefore after pulling a few work string joints out of the hole, the cement inside the stinger is fully displaced with spacer while cement slurry still is left in the annulus. This phenomenon is shown step by step in Fig. 7.12.

Some alternatives are suggested to minimize the effect of dynamic conditions imposed by pulling out of the hole: using a model to correctly calculate the volume of spacer ahead and behind the cement slurry, eliminating the use of stinger, and/or using mechanical devices in the drillpipe just above the stinger [50]. To minimize the plug contamination due to its movement while it sets, it is recommended to use a gelled fluid pill or a mechanical foundation.

*Cement job monitoring*—The recording of pressure, slurry rate, density, and integrated volume (e.g. mud return rate compared with pump rate) in real time gives a better understanding of the job execution [51, 52]. These data can be analyzed and used for other jobs especially in a campaign plug placement. Figure 7.13 shows the framework of a process control loop for eliminating future plug failures.

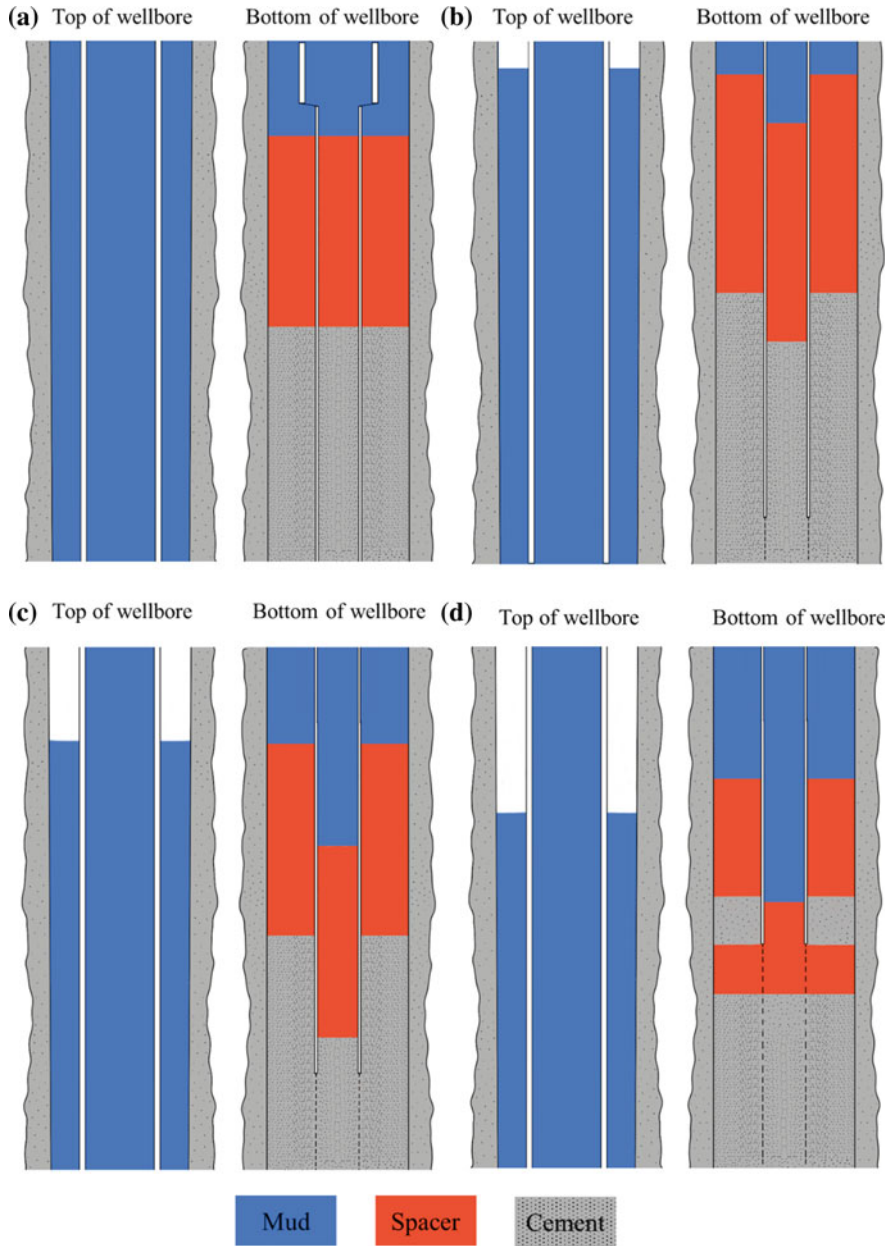
## 7.5 Verification of Placement Operation

*Position verification*—When a cement plug is placed at the desired interval, its depth and sealability need to be verified. When cement is set, it is *dressed off* and the top of cement is identified by tagging. Cement plugs placed on a mechanical foundations are not tagged when the depth of plug has been verified.

*Sealing verification*—The evaluation of plug sealing capability is conducted by either pressure testing, or weight testing based on the elements of the well barrier envelope.

*Pressure testing*—Plugs installed inside casing are placed on either mechanical plugs or viscous pills, Fig. 7.14. When the mechanical plug is used as foundation and it passes the pressure test, usually the cement installed on top of it is not pressure tested. However, if the mechanical plug is not pressure tested or fails to pass the pressure test, the installed plug is pressure tested.

When a cement plug is installed on a viscous pill, its sealability is evaluated by performing either positive or negative pressure testing. In a positive pressure test the well is subjected to a given pressure and the pressure changes are recorded. The given pressure is higher than the pressure below the plug, Fig. 7.15a. When considering a positive test, the primary cement (cement behind casing), cement-pipe bonding, and casing should not be damaged. To avoid this issue, the test pressure is selected to not exceed the casing strength minus wear allowance. Another factor to be considered during positive pressure testing is the effect of ballooning uncemented casing. It happens when the test pressure exceeds the casing mechanical limit and casing is expanded in the intervals where liquid fills the annulus behind the casing. In this case



**Fig. 7.12** An unbalanced condition during pulling the work string equipped with stinger out of hole: **a** Balanced-plug is established while workstring is inside plug, **b** workstring is removed slowly from the plug but due to the removed volume of workstring, the height of spacer inside and outside is not in the same level, **c** the more the workstring is run out of hole, the higher the differences of the fluid levels **d** spacer reaches the tailpipe while the annular cement slurry is still left [50]

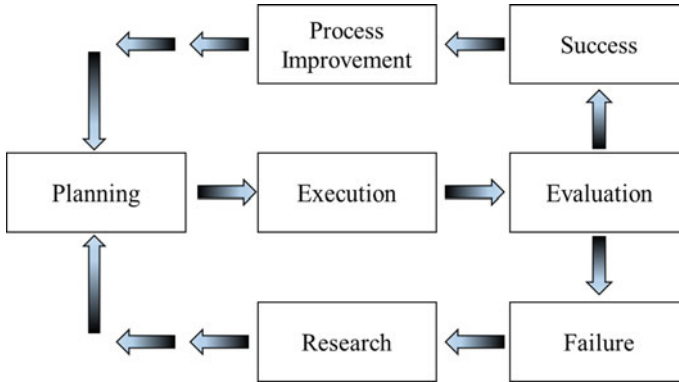


Fig. 7.13 Process control loop for a plug placement operation [53]

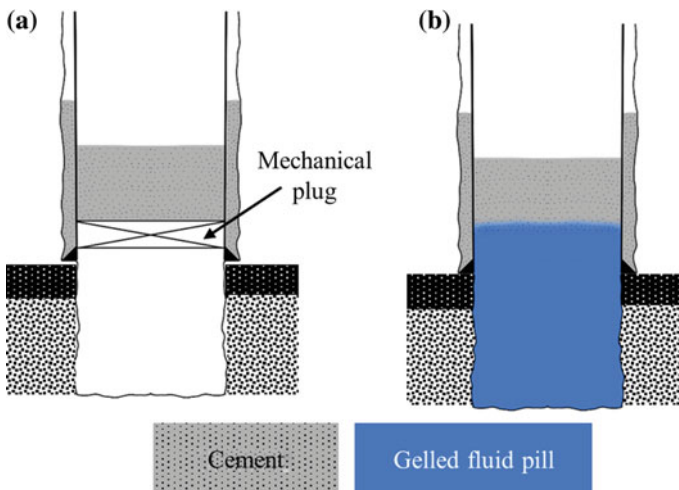
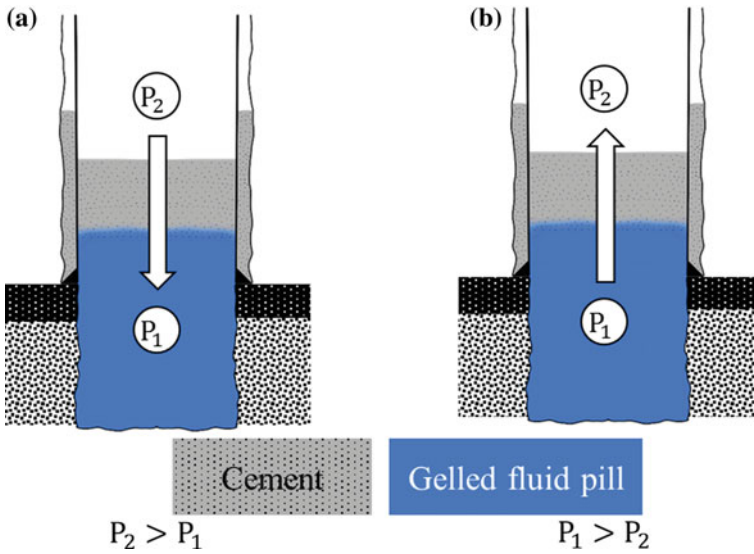


Fig. 7.14 Pressure testing of a cement plug placed inside casing; **a** plug placed on a mechanical foundation, **b** plug placed on a viscous pill

as the test-pressure increases, a portion of injected fluid fills the volume created due to ballooning however, it may be misinterpreted and lead to disqualifying the plug. Pressure testing of cement plug is reviewed in Chap. 9.

In a negative pressure test, the well pressure is dropped and the pressure build-up is recorded. In other words, pressure below the installed plug is higher than the pressure above the plug, Fig. 7.15b. The negative pressure test is also known by other names such as *inflow test* or *drawdown test*. Table 7.2 summarizes requirements for pressure testing of different regulatory authorities.

*Weight testing*—This method is used for plugs installed in open holes as pressure testing in open holes is meaningless. In this method, top of cement is dressed off

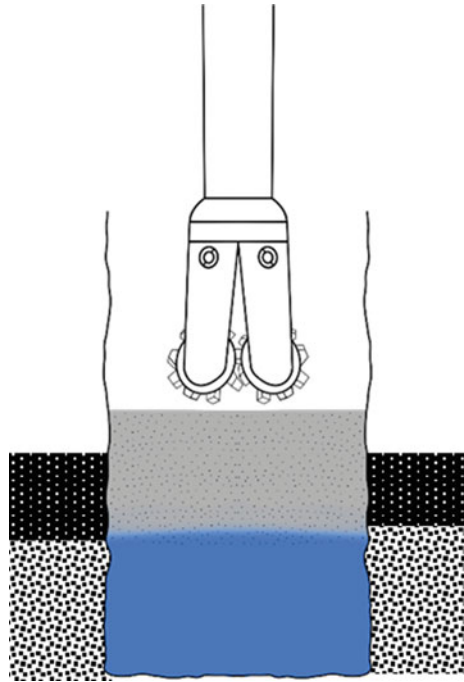


**Fig. 7.15** Pressure testing of an installed plug inside casing; **a** positive pressure testing, **b** negative pressure testing

**Table 7.2** Requirements for pressure testing and weight testing variation for some countries

Country	Pressure testing requirement	Weight testing requirement
Norway [54]	<ul style="list-style-type: none"> <li>The positive pressure test requirement is 1000 psi above the estimated leak off pressure (below casing/potential leak path)</li> <li>The positive pressure test requirement for a surface casing plug is 500 psi above the estimated leak off pressure</li> <li>Cement plug installed on a pressure tested foundation need not to be pressure tested</li> </ul>	<ul style="list-style-type: none"> <li>Cement plug installed in an openhole should be weight tested</li> </ul>
United Kingdom [55]	<ul style="list-style-type: none"> <li>The positive pressure test requirement is minimum 500 psi above the source pressure</li> <li>Inflow test requirement at least the maximum pressure differential which barrier will experience after permanent abandonment</li> </ul>	<ul style="list-style-type: none"> <li>Cement plug installed in open hole is weight tested by drillpipe with typically 10–15 klbs</li> <li>When cement plug installed in open hole is weight tested by wireline, coiled tubing or stinger then the weight is limited by tools and geometry</li> </ul>

**Fig. 7.16** Weight testing of a plug installed in an openhole



and a weight is applied on the plug, Fig. 7.16. Drillpipe, coiled tubing, stinger, and wireline can be used for weight testing however, the application of stinger, wireline, and coiled tubing is limited by weight of the tools or geometry. Different regulators have different weight requirements. Table 7.2 summarizes some specific requirements for weight testing of different regulatory authorities.

The cement plug installed inside tubing is usually verified by pressure testing and tagging. If the plug is installed on a pressure tested bridge plug, then it is not pressure tested. As the plug is installed on a tested bridge plug, its position verification and pressure testing are not possible. Sealing capability of cement plugs installed between tubing and production casing is verified by pressure testing and position verification is done by bond logging.

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