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LEARNING OBJECTIVES:

Having worked through this chapter the student will be able to:

General
• Describe the principal functions of cement.

Cement Slurries
• List and describe the major properties of a cement slurry.
• Describe the additives used in cement slurries and the way in which they affect the properties of the slurry.

Cementing Operations
• Calculate the volume of slurry, cement, mixwater, displacing fluid required for a single stage and two-stage cementing operation.
• Calculate the bottomhole pressures generated during the above cementing operations.
• Describe the surface and downhole equipment used in a single, two-stage and liner cementation operation.
• Prepare a program for a single and two stage cementing operation and describe the ways in which a good cement bond can be achieved.

Cement Plugs
• Describe the reasons for setting cement plugs.
• Describe the principal methods for placing a cement plug in casing or open hole.
• Calculate the displacement volumes for an underbalanced cement plug.

Evaluation of Cementing Operations
• Describe the principles involved and the tools and techniques used to evaluate the quality of a cementing operation.
• Discuss the limitations of the above techniques.
1. INTRODUCTION
Cement is used primarily as an impermeable seal material in oil and gas well drilling. It is most widely used as a seal between casing and the borehole, bonding the casing to the formation and providing a barrier to the flow of fluids from, or into, the formations behind the casing and from, and into, the subsequent hole section (Figure 1). Cement is also used for remedial or repair work on producing wells. It is used for instance to seal off perforated casing when a producing zone starts to produce large amounts of water and/or to repair casing leaks. This chapter will present: the reasons for using cement in oil and gas well drilling; the design of the cement slurry; and the operations involved in the placement of the cement slurry. The methods used to determine if the cementing operation has been successful will also be discussed.

1.1 Functions of oilwell cement
There are many reasons for using cement in oil and gaswell operations. As stated above, cement is most widely used as a seal between casing and the borehole, bonding the casing to the formation and providing a barrier to the flow of fluids from, or into, the formations behind the casing and from, and into, the subsequent hole section (Figure 1). However, when placed between the casing and borehole the cement may be required to perform some other tasks. The most important functions of a cement sheath between the casing and borehole are:

- To prevent the movement of fluids from one formation to another or from the formations to surface (through the annulus between the casing and borehole).
- To support the casing (specifically surface casing).
- To protect the casing from corrosive fluids in the formations.

However, the prevention of fluid migration is by far the most important function of the cement sheath between the casing and borehole. Cement is only required to support the casing in the case of the surface casing where the axial loads on the casing, due to the weight of the wellhead and BOP connected to the top of the casing string, are extremely high. The cement sheath in this case prevents the casing from buckling.

The techniques used to place the cement in the annular space will be discussed in detail later but basically the method of doing this is to pump cement down the inside of the casing and through the casing shoe into the annulus (Figure 2). This operation is known as a primary cement job. A successful primary cement job is essential to allow further drilling and production operations to proceed.
Figure 1 Functions of Primary Cementing

Figure 2 Primary Cementing Operations
Another type of cement job that is performed in oil and gas well operations is called a **secondary or squeeze cement job**. This type of cement job may have to be done at a later stage in the life of the well. A secondary cement job may be performed for many reasons, but is usually carried out on wells which have been producing for some time. They are generally part of remedial work on the well (e.g. sealing off water producing zones or repairing casing leaks). These cement jobs are often called squeeze cement jobs because they involve cement being forced through holes or perforations in the casing into the annulus and/or the formation (Figure 3).

The specific properties of the cement slurry which is used in the primary and secondary cementing operations discussed above will depend on the particular reason for using the cement (e.g. to plug off the entire wellbore or simply to plug off perforations) and the conditions under which it will be used (e.g. the pressure and temperature at the bottom of the well).

The cement slurry which is used in the above operations is made up from: cement powder; water; and chemical additives. There are many different grades of cement powder manufactured and each has particular attributes which make it suitable for a particular type of operation. These grades of cement powder will be discussed below. The water used may be fresh or salt water. The chemical additives (Figure
4) which are mixed into the cement slurry alter the properties of both the cement slurry and the hardened cement and will be discussed at length in Section 3 below.

![Diagram of cement slurry components]

**Table 1 Composition of API Cements**

<table>
<thead>
<tr>
<th>Compounds*</th>
<th>Fineness</th>
<th>API Class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C3S</td>
</tr>
<tr>
<td>A</td>
<td>53</td>
<td>24</td>
</tr>
<tr>
<td>B</td>
<td>44</td>
<td>32</td>
</tr>
<tr>
<td>C</td>
<td>58</td>
<td>16</td>
</tr>
<tr>
<td>D&amp;E</td>
<td>50</td>
<td>26</td>
</tr>
<tr>
<td>G</td>
<td>52</td>
<td>27</td>
</tr>
<tr>
<td>H</td>
<td>52</td>
<td>25</td>
</tr>
</tbody>
</table>

*Plus free lime, alkali, (Na, K, Mg)

Each cement job must be carefully planned to ensure that the correct cement and additives are being used, and that a suitable placement technique is being employed for that particular application. In planning the cement job the engineer must ensure that:

- The cement can be placed correctly using the equipment available
- The cement will achieve adequate compressive strength soon after it is placed
- The cement will thereafter isolate zones and support the casing throughout the life of the well

To assist the engineer in designing the cement slurry, the cement slurry is tested in the laboratory under the conditions to which it will be exposed in the wellbore. Theses tests are known as pilot tests and are carried out before the job goes ahead. These tests must simulate downhole conditions as closely as possible. They will
help to assess the effect of different amounts of additives on the properties of the cement (e.g. thickening time, compressive strength development etc).

<table>
<thead>
<tr>
<th>API Class</th>
<th>Mixwater (Gals/Sk.)</th>
<th>Shurry Weight (Lbs/Gal.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.2</td>
<td>15.6</td>
</tr>
<tr>
<td>B</td>
<td>5.2</td>
<td>15.6</td>
</tr>
<tr>
<td>C</td>
<td>6.3</td>
<td>14.8</td>
</tr>
<tr>
<td>D</td>
<td>4.3</td>
<td>16.4</td>
</tr>
<tr>
<td>E</td>
<td>4.3</td>
<td>16.4</td>
</tr>
<tr>
<td>F</td>
<td>4.3</td>
<td>16.2</td>
</tr>
<tr>
<td>G</td>
<td>5.0</td>
<td>15.8</td>
</tr>
<tr>
<td>H</td>
<td>4.3</td>
<td>16.4</td>
</tr>
</tbody>
</table>

Table 2 API Mixwater requirements for API cements

1.2 Classification of cement powders
There are several classes of cement powders which are approved for oilwell drilling applications, by the American Petroleum Institute (API). Each of these cement powders have different properties when mixed with water. The difference in properties produced by the cement powders is caused by the differences in the distribution of the four basic compounds used to make cement powder; C₃S, C₂S, C₃A and C₄AF (Table 1).

Classes A and B - These cements are cheaper than other classes of cement and can only be used at shallow depths. There are no special requirements. Class B has a higher resistance to sulphate than Class A.

Class C - This cement has a high C₃S content and therefore becomes hard relatively quickly.

Classes D, E and F - These are known as retarder cements since they take a much longer time to set hard than the normal cement powder. This retardation is due to a coarser grind. These cements are more expensive than the other classes of cement and are not used unless justified by their ability to work satisfactorily under high temperatures and pressures.

Class G and H - These are general purpose cement powders which are compatible with most additives and can be used under a wide range of temperature and pressure. Class G is the most common cement type used in most areas. Class H has a coarser grind than Class G and gives better retarding properties in deeper wells.

There are other, non-API, terms used to classify cement. These include the following:

- **Pozmix cement** - This is formed by mixing Portland cement with pozzolan (ground volcanic ash) and 2% bentonite. This is a very lightweight but durable cement. Pozmix cement is less expensive than most other types of cement and due to its light weight is often used for shallow well casing cementation operations.
<table>
<thead>
<tr>
<th>Water, gal/sk.</th>
<th>Portland</th>
<th>API Class G</th>
<th>API Class H</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.19</td>
<td>4.97</td>
<td>4.29</td>
</tr>
<tr>
<td>Slurry Wt, lb/gal.</td>
<td>15.9</td>
<td>15.8</td>
<td>16.5</td>
</tr>
<tr>
<td>Slurry Vol, cuft/sk.</td>
<td>1.8</td>
<td>1.14</td>
<td>1.05</td>
</tr>
<tr>
<td>Temp. (deg. F)</td>
<td>Pressure (psi)</td>
<td>Typical comp. strength (psi) @ 12hrs</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0</td>
<td>615</td>
<td>440</td>
</tr>
<tr>
<td>80</td>
<td>0</td>
<td>1470</td>
<td>1185</td>
</tr>
<tr>
<td>95</td>
<td>800</td>
<td>2085</td>
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<td>1600</td>
<td>2925</td>
<td>2915</td>
</tr>
<tr>
<td>140</td>
<td>3000</td>
<td>5050</td>
<td>4200</td>
</tr>
<tr>
<td>170</td>
<td>3000</td>
<td>5920</td>
<td>4380</td>
</tr>
<tr>
<td>200</td>
<td>3000</td>
<td>-</td>
<td>5110</td>
</tr>
<tr>
<td>Typical comp. strength (psi) @ 24hrs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0</td>
<td>2870</td>
<td>-</td>
</tr>
<tr>
<td>80</td>
<td>0</td>
<td>4130</td>
<td>-</td>
</tr>
<tr>
<td>95</td>
<td>800</td>
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<td>110</td>
<td>1600</td>
<td>5840</td>
<td>-</td>
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<td>140</td>
<td>3000</td>
<td>6550</td>
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<td>170</td>
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<tr>
<td>200</td>
<td>3000</td>
<td>-</td>
<td>7360</td>
</tr>
</tbody>
</table>

Table 3 Compressive strength of cements

- **Gypsum Cement** - This type of cement is formed by mixing Portland cement with gypsum. These cements develop a high early strength and can be used for remedial work. They expand on setting and deteriorate in the presence of water and are therefore useful for sealing off lost circulation zones.

- **Diesel oil cement** - This is a mixture of one of the basic cement classes (A, B, G, H), diesel oil or kerosene and a surfactant. These cements have unlimited setting times and will only set in the presence of water. Consequently they are often used to seal off water producing zones, where they absorb and set to form a dense hard cement.

**1.3 Mixwater Requirements**
The water which is used to make up the cement slurry is known as the *mixwater*. The amount of mixwater used to make up the cement slurry is shown in Table 2. These amounts are based on:

- The need to have a slurry that is easily pumped.
- The need to hydrate all of the cement powder so that a high quality hardened cement is produced.
- The need to ensure that all of the free water is used to hydrate the cement powder and that no free water is present in the hardened cement.
The amount of mixwater that is used to make up the cement slurry is carefully controlled. If too much mixwater is used the cement will not set into a strong, impermeable cement barrier. If not enough mixwater is used:

- The slurry density and viscosity will increase.
- The pumpability will decrease
- Less volume of slurry will be obtained from each sack of cement

The quantities of mixwater quoted in Table 2 are average values for the different classes of cement. Sometimes the amount of mixwater used will be changed to meet the specific temperature and pressure conditions which will be experienced during the cement job.

2. **Properties of Cement**

The properties of a specific cement slurry will depend on the particular reason for using the cement, as discussed above. However, there are fundamental properties which must be considered when designing any cement slurry.

(a) **Compressive strength**

The casing shoe should not be drilled out until the cement sheath has reached a compressive strength of about 500 psi. This is generally considered to be enough to support a casing string and to allow drilling to proceed without the hardened cement sheath, disintegrating, due to vibration. If the operation is delayed whilst waiting on the cement to set and develop this compressive strength the drilling rig is said to be “waiting on cement” (WOC). The development of compressive strength is a function of several variables, such as: temperature; pressure; amount of mixwater added; and elapsed time since mixing.

The setting time of a cement slurry can be controlled with chemical additives, known as **accelerators**. Table 3 shows the compressive strengths for different cements under varying conditions.

(b) **Thickening time (pumpability)**

The thickening time of a cement slurry is the time during which the cement slurry can be pumped and displaced into the annulus (i.e. the slurry is pumpable during this time). The slurry should have sufficient thickening time to allow it to be:

- Mixed
- Pumped into the casing
- Displaced by drilling fluid until it is in the required place

Generally 2 - 3 hours thickening time is enough to allow the above operations to be completed. This also allows enough time for any delays and interruptions in the cementing operation. The thickening time that is required for a particular operation will be carefully selected so that the following operational issues are satisfied:

- The cement slurry does not set whilst it is being pumped
- The cement slurry is not sitting in position as a slurry for long periods, potentially being contaminated by the formation fluids or other contaminants
• The rig is not waiting on cement for long periods.

Wellbore conditions have a significant effect on thickening time. An increase in temperature, pressure or fluid loss will each reduce the thickening time and these conditions will be simulated when the cement slurry is being formulated and tested in the laboratory before the operation is performed.

(c) Slurry density
The standard slurry densities shown in Table 2 may have to be altered to meet specific operational requirements (e.g. a low strength formation may not be able to support the hydrostatic pressure of a cement slurry whose density is around 15 ppg). The density can be altered by changing the amount of mixwater or using additives to the cement slurry. Most slurry densities vary between 11 - 18.5 ppg. It should be noted that these densities are relatively high when the normal formation pore pressure gradient is generally considered to be equivalent to 8.9 ppg. It is generally the case that cement slurries generally have a much higher density than the drilling fluids which are being used to drill the well. The high slurry densities are however unavoidable if a hardened cement with a high compressive strength is to be achieved.

(d) Water loss
The slurry setting process is the result of the cement powder being hydrated by the mixwater. If water is lost from the cement slurry before it reaches its intended position in the annulus its pumpability will decrease and water sensitive formations may be adversely affected. The amount of water loss that can be tolerated depends on the type of cement job and the cement slurry formulation.

Squeeze cementing requires a low water loss since the cement must be squeezed before the filter cake builds up and blocks the perforations. Primary cementing is not so critically dependent on fluid loss. The amount of fluid loss from a particular slurry should be determined from laboratory tests. Under standard laboratory conditions (1000 psi filter pressure, with a 325 mesh filter) a slurry for a squeeze job should give a fluid loss of 50 - 200 cc. For a primary cement job 250 - 400 cc is adequate.

(e) Corrosion resistance
Formation water contains certain corrosive elements which may cause deterioration of the cement sheath. Two compounds which are commonly found in formation waters are sodium sulphate and magnesium sulphate. These will react with lime and C₃S to form large crystals of calcium sulphaaluminate. These crystals expand and cause cracks to develop in the cement structure. Lowering the C₃A content of the cement increases the sulphate resistance. For high sulphate resistant cement the C₃A content should be 0 - 3%

(f) Permeability
After the cement has hardened the permeability is very low (<0.1 millidarcy). This is much lower than most producing formations. However if the cement is disturbed during setting (e.g. by gas intrusion) higher permeability channels (5 - 10 darcies) may be created during the placement operation.
3. CEMENT ADDITIVES

Most cement slurries will contain some additives, to modify the properties of the slurry and optimise the cement job. Most additives are known by the trade-names used by the cement service companies. Cement additives can be used to:

- Vary the slurry density
- Change the compressive strength
- Accelerate or retard the setting time
- Control filtration and fluid loss
- Reduce slurry viscosity

Additives may be delivered to the rig in granular or liquid form and may be blended with the cement powder or added to the mixwater before the slurry is mixed. The amount of additive used is usually given in terms of a percentage by weight of the cement powder (based on each sack of cement weighing 94 lb). Several additives will affect more than one property and so care must be taken as to how they are used (Figure 4).
It should be remembered that the slurry is mixed up and tested in the laboratory before the actual cement job.

(a) Accelerators
Accelerators are added to the cement slurry to shorten the time taken for the cement to set. These are used when the setting time for the cement would be much longer than that required to mix and place the slurry, and the drilling rig would incur WOC time. Accelerators are especially important in shallow wells where temperatures are low and therefore the slurry may take a long time to set. In deeper wells the higher temperatures promote the setting process, and accelerators may not be necessary.

The most common types of accelerator are:

- Calcium chloride (CaCl₂) 1.5 - 2.0%
- Sodium chloride (NaCl) 2.0 - 2.5%
- Seawater

It should be noted that at higher concentrations these additives will act as retarders.

(b) Retarders
In deep wells the higher temperatures will reduce the cement slurry’s thickening time. Retarders are used to prolong the thickening time and avoid the risk of the cement setting in the casing prematurely. The bottom hole temperature is the critical factor which influences slurry setting times and therefore for determining the need for retarders. Above a static temperature of 260 - 275 degrees F the effect of retarders should be measured in pilot tests.

The most common types of retarders are:

- Calcium lignosulphanate (sometimes with organic acids) 0.1 - 1.5%
- Saturated Salt Solutions

(c) Lightweight additives (Extenders)
Extenders are used to reduce slurry density for jobs where the hydrostatic head of the cement slurry may exceed the fracture strength of certain formations. In reducing the slurry density the ultimate compressive strength is also reduced and the thickening time increased. The use of these additives allows more mixwater to be added, and hence increases the amount of slurry which is produced by each sack of cement powder (the yield of the slurry). Such additives are therefore sometimes called extenders.

The most common types of lightweight additives are:

- Bentonite (2 - 16%) - This is by far the most common type of additive used to lower slurry density. The bentonite material absorbs water, and therefore allows more mixwater to be added. Bentonite will also however reduce compressive strength and sulphate resistance. The increased yield due to the bentonite added is shown in Table 4.
• Pozzolan - This may be used in a 50/50 mix with the Portland cement. The result is a slight decrease in compressive strength, and increased sulphate resistance.

• Diatomaceous earth (10 - 40%) - The large surface area of diatomaceous earth allows more water absorption, and produces low density slurries (down to 11 ppg).

(d) Heavyweight additives
Heavyweight additives are used when cementing through overpressured zones. The most common types of additive are:

• Barite (barium sulphate) - this can be used to attain slurry densities of up to 18 ppg. It also causes a reduction in strength and pumpability.

• Hematite ($\text{Fe}_2\text{O}_3$) - The high specific gravity of hematite can be used to raise slurry densities to 22 ppg. Hematite significantly reduces the pumpability of slurries and therefore friction reducing additives may be required when using hematite.

• Sand - graded sand (40 - 60 mesh) can give a 2 ppg increase in slurry density.

(e) Fluid loss additives
Fluid loss additives are used to prevent dehydration of the cement slurry and premature setting. The most common additives are:

• Organic polymers (cellulose) 0.5 - 1.5%

• Carboxymethyl hydroxyethyl cellulose (CMHEC) 0.3 - 1.0%

(CMHEC will also act as a retarder)

(f) Friction reducing additives (Dispersants)
Dispersants are added to improve the flow properties of the slurry. In particular they will lower the viscosity of the slurry so that turbulence will occur at a lower circulating pressure, thereby reducing the risk of breaking down formations. The most commonly used are:

• Polymers 0.3 - 0.5 lb sx of cement
• Salt 1 - 16 lb sx
• Calcium lignosulphanate 0.5 - 1.5 lb sx

(g) Mud contaminates
As well as the compounds deliberately added to the slurry on surface, to improve the slurry properties, the cement slurry will also come into contact with, and be contaminated by, drilling mud when it is pumped downhole. The chemicals in the mud may react with the cement to give undesirable side effects. Some of these are listed below:

<table>
<thead>
<tr>
<th>Mud additive</th>
<th>Effect on cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>barite</td>
<td>increases density and reduces</td>
</tr>
<tr>
<td></td>
<td>compressive strength</td>
</tr>
<tr>
<td>caustic</td>
<td>acts as an accelerator</td>
</tr>
</tbody>
</table>
calcium compounds decrease density
diesel oil decrease density
thinner act as retarders

The mixture of mud and cement causes a sharp increase in viscosity. The major effect of a highly viscous fluid in the annulus is that it forms channels which are not easily displaced. These channels prevent a good cement bond all round the casing.

To prevent mud contamination of the cement a spacer fluid is pumped ahead of the cement slurry.

4. PRIMARY CEMENTING

The objective of a primary cement job is to place the cement slurry in the annulus behind the casing. In most cases this can be done in a single operation, by pumping cement down the casing, through the casing shoe and up into the annulus. However, in longer casing strings and in particular where the formations are weak and may not be able to support the hydrostatic pressure generated by a very long colom of cement slurry, the cement job may be carried out in two stages. The first stage is completed in the manner described above, with the exception that the cement slurry does not fill the entire annulus, but reaches only a pre-determined height above the shoe. The second stage is carried out by including a special tool in the casing string which can be opened, allowing cement to be pumped from the casing and into the annulus. This tool is called a multi stage cementing tool and is placed in the casing string at the point at which the bottom of the second stage is required. When the second stage slurry is ready to be pumped the multi stage tool is opened and the second stage slurry is pumped down the casing, through the stage cementing tool and into the annulus, as in the first stage. When the required amount of slurry has been pumped, the multi stage tool is closed. This is known as a two stage cementing operation and will be discussed in more detail later.

The height of the cement sheath, above the casing shoe, in the annulus depends on the particular objectives of the cementing operations. In the case of conductor and surface casing the whole annulus is generally cemented so that the casing is prevented from buckling under the very high axial loads produced by the weight of the wellhead and BOP. In the case of the intermediate and production casing the top of the cement sheath (Top of Cement - TOC) is generally selected to be approximately 300-500 ft. above any formation that could cause problems in the annulus of the casing string being cemented. For instance, formations that contain gas which could migrate to surface in the annulus would be covered by the cement. Liners are generally cemented over their entire length, all the way from the liner shoe to the liner hanger.

4.1 Downhole cementing equipment

In order to carry out a conventional primary cement job some special equipment must be included in the casing string as it is run.
• Guide shoe - A guide (Figure 5) shoe is run on the bottom of the first joint of casing. It has a rounded nose to guide the casing past any ledges or other irregularities in the hole.

![Diagram of Guide shoe and float shoe](image)

*Figure 5 Guide shoe and float shoe*

• Float collar - A float collar (Figure 6) is positioned 1 or 2 joints above the guide shoe. It acts as a seat for the cement plugs used in the pumping and displacement of the cement slurry. This means that at the end of the cement job there will be some cement left in the casing between the float collar and the guide shoe which must be drilled out.

The float collar also contains a non-return valve so that the cement slurry cannot flow back up the casing. This is necessary because the cement slurry in the annulus generally has a higher density than the displacing fluid in the casing, therefore a U-tube effect is created when the cement is in position and the pumps are stopped. Sometimes the guide shoe also has a non-return valve as an extra precaution. It is essential that the non-return valves are effective in holding back the cement slurry.
The use of a non-return valve means that as the casing is being run into the borehole the fluid in the hole cannot enter the casing from below. This creates a buoyancy effect which can be reduced by filling up the casing from the surface at regular intervals while the casing is being run (every 5 - 20 joints). This filling up process increases the running in time and can be avoided by the use of automatic or differential fill up devices fitted to the float collar or shoe. These devices allow a controlled amount of fluid to enter the casing at the bottom of the string. The ports through which the fluid enters are blocked off before the cement job begins. The use of a differential fill-up device also reduces the effect of surge pressures on the formation.

- Centralisers - these are hinged metal ribs which are installed on the casing string as it is run (Figure 7). Their function is to keep the casing away from the borehole so that there is some annular clearance around the entire circumference of the casing.

The proper use of centralisers will help to:

- Improve displacement efficiency (i.e. place cement all the way around the casing)
- Prevent differential sticking
- Keep casing out of keyseats
Centralisers are particularly required in deviated wells where the casing tends to lie on the low side of the hole. On the high side there will be little resistance to flow, and so cement placement will tend to flow up the high side annular space. Mud channels will tend to form on the low side of the hole, preventing a good cement job. Each centraliser is hinged so that it can be easily clamped onto the outside of the casing and secured by a retaining pin. The centraliser is prevented from moving up and down the casing by positioning the centraliser across a casing coupling or a collar known as a stop collar. The spacing of centralisers will vary depending on the requirements of each cement job. In critical zones, and in highly deviated parts of the well, they are closely spaced, while on other parts of the casing string they may not be necessary at all. A typical programme might be:

1 centraliser immediately above the shoe
1 every joint on the bottom 3 joints
1 every joint through the production zone
1 every 3 joints elsewhere

*Figure 7 Casing Centraliser*

- Wipers/scratchers - these are devices run on the outside of the casing to remove mud cake and break up gelled mud. They are sometimes used through the production zone.
4.2 Surface cementing equipment

Mixing and pumping facilities:

On most rigs cement powder and additives are handled in bulk, which makes blending and mixing much easier. For large volume cement jobs several bulk storage bins may be required on the rig. On offshore rigs the cement is transferred pneumatically from supply boats to the storage bins.

For any cement job there must be sufficient water available to mix the slurry at the desired water/cement ratio when required. The mix water must also be free of all contaminants.

The water is added to the cement in a jet mixer (Figure 8). The mixer consists of a funnel shaped hopper, a mixing bowl, a water supply line and an outlet for the slurry. As the mixwater is pumped across the lower end of the hopper a venturi effect is created and cement powder is drawn down into the flow of mixwater and a slurry is created. The slurry flows into a slurry tub where its density is measured. The density of the slurry should be regularly checked during the cement job since this is the primary means by which the quality of the slurry is determined. If the density of the slurry is correct then the correct amount of mixwater has been mixed with the cement powder. Samples can be taken directly from the mixer and weighed in a standard mud balance or automatic devices (densometers) can also be used.

Various types of cement pumping units are available. For land based jobs they can be mounted on a truck, while skid mounted units are used offshore. The unit normally has twin pumps (triplex, positive displacement) which may be diesel powered or driven by electric motors. These units can operate at high pressures (up to 20,000 psi) but are generally limited to low pumping rates. Most units are capable of mixing and displacing 50 - 70 cubic feet of slurry per minute. In order to minimise contamination by the mud in the annulus a preflush or spacer fluid is pumped ahead of the cement slurry. The actual composition of the spacer depends...
on the type of mud being used. For water based muds the spacer fluid is often just water, but specially designed fluids are available. The volume of spacer is based on the need to provide sufficient separation of mud and cement in the annulus (20 - 50 bbls of spacer is common).

![Figure 9 Cement Head](image)

**Cementing heads:**
The cement head provides the connection between the discharge line from the cement unit and the top of the casing (Figure 9). This piece of equipment is designed to hold the cement plugs used in the conventional primary cement job. The cement head makes it possible to release the bottom plug, mix and pump down the cement slurry, release the top plug and displace the cement without making or breaking the connection to the top of the casing. For ease of operation the cement head should be installed as close to rig floor level as possible. The cement jobs will be unsuccessful if the cement plugs are installed in the correct sequence or are not released from the cementing head.

Mud is normally used to displace the cement slurry. The cement pumps or the rig pumps may be used for the displacement. It is recommended that the cement slurry is displaced at as high a rate as possible. High rate displacement will aid efficient mud displacement. It is highly unlikely that it will be possible to achieve turbulence in the cement slurry since it is so viscous and has such a high density. However, it may be possible to generate turbulence in the spacer and this will result in a more efficient displacement of the mud.
4.3 Single Stage Cementing Operation

The single stage primary cementing operation is the most common type of cementing operation that is conducted when drilling a well. The procedure for performing a single stage cementing operation (Figure 10) will be discussed first and then the procedure for conducting a **multiple stage and stinger cementing** operations will be discussed.

![Figure 10 Single Stage Cementing Operation](image)

In the case of the single stage operation, the casing with all of the required cementing accessories such as the float collar, centralisers etc. is run in the hole until the shoe is just a few feet off the bottom of the hole and the casing head is connected to the top of the casing. It is essential that the cement plugs are correctly placed in the cement head. The casing is then circulated clean before the cementing operation begins (at least one casing volume should be circulated). The first cement plug (**wiper plug**) shown in Figure 11, is pumped down ahead of the cement to wipe the inside of the casing clean. The spacer is then pumped into the casing. The spacer is followed by the cement slurry and this is followed by the second plug (**shut-off plug**) shown in Figure 12. When the wiper plug reaches the float collar its rubber diaphragm is ruptured, allowing the cement slurry to flow through the plug, around the shoe, and up into the annulus. At this stage the spacer is providing a barrier to mixing of the cement and mud. When the solid, shut-off plug reaches the float collar it lands on the wiper plug and stops the displacement process. The pumping rate should be slowed down as the shut-off plug approaches the float collar and the shut-off plug should be gently **bumped** into the bottom, wiper plug. The casing is often pressure tested at this point in the operation. The pressure is then bled off slowly to ensure that the float valves, in the float collar and/or casing shoe, are holding.
The displacement of the top plug is closely monitored. The volume of displacing fluid necessary to bump the plug should be calculated before the job begins. When the pre-determined volume has almost been completely pumped, the pumps should be slowed down to avoid excessive pressure when the plug is bumped. If the top plug does not bump at the calculated volume (allowing for compression of the mud) this may be because the top, shut-off plug has not been released. If this is the case, no more fluid should be pumped, since this would displace the cement around the casing shoe and up the annulus. Throughout the cement job the mud returns from the annulus should be monitored to ensure that the formation has not been broken down. If formation breakdown does occur then mud returns would slow down or stop during the displacement operation.

The single stage process can be summarised as follows:

1. Circulate the casing and annulus (one casing volume pumped)
2. Release wiper plug
3. Pump spacer
4. Pump cement
5. Release shut-off plug
6. Displace with displacing fluid until the shut-off plug lands on the float collar
7. Pressure test the casing

![Rupture Disk](image)

Figure 11 Bottom Plug (wiper plug)
4.4 Multi-Stage Cementing Operation

When a long intermediate string of casing is to be cemented it is sometimes necessary to split the cement sheath in the annulus into two, with one sheath extending from the casing shoe to some point above potentially troublesome formations at the bottom of the hole, and the second sheath covering shallower troublesome formations. The placement of these cement sheaths is known as a multi-stage cementing operation (Figure 13). The reasons for using a multi-stage operation are to reduce:

- Long pumping times
- High pump pressures
- Excessive hydrostatic pressure on weak formations due to the relatively high density of cement slurries.
The procedure for conducting a multi-stage operation is as follows:

**First stage**
The procedure for the first stage of the operation is similar to that described in Section 4.3 above, except that a wiper plug is not used and only a liquid spacer is pumped ahead of the cement slurry. The conventional shut-off plug is replaced by a plug with flexible blades. This type of shut-off plug is used because it has to pass through the stage cementing collar which will be discussed below. It is worth noting that a smaller volume of cement slurry is used, since only the lower part of the annulus is to be cemented. The height of this cemented part of the annulus will depend on the fracture gradient of the formations which are exposed in the annulus (a height of 3000' - 4000' above the shoe is common).

**Second stage**
The second stage of the operation involves the use of a special tool known as a stage collar (Figure 14), which is made up into the casing string at a pre-determined position. The position often corresponds to the depth of the previous casing shoe. The ports in the stage collar are initially sealed off by the inner sleeve. This sleeve is held in place by retaining pins. After the first stage is complete a special dart is released from surface which lands in the inner sleeve of the stage collar. When a pressure of 1000 - 1500 psi is applied to the casing above the dart, and therefore to the dart, the retaining pins on the inner sleeve are sheared and the sleeve moves...
down, uncovering the ports in the outer mandrel. Circulation is established through the stage collar before the second stage slurry is pumped.

The normal procedure for the second stage of a two stage operation is as follows:

1. Drop opening dart
2. Pressure up to shear pins
3. Circulate though stage collar whilst the first stage cement is setting
4. Pump spacer
5. Pump second stage slurry
6. Release closing plug
7. Displace plug and cement with mud
8. Pressure up on plug to close ports in stage collar and pressure test the casing.

![Multi-Stage Cementing Collar](image)

**Figure 14** Multi-Stage Cementing Collar

To prevent cement falling down the annulus a cement basket or packer may be run on the casing below the stage collar. If necessary, more than one stage collar can be run on the casing so that various sections of the annulus can be cemented. One disadvantage of stage cementing is that the casing cannot be moved after the first stage cement has set in the lower part of the annulus. This increases the risk of channelling and a poor cement bond.
4.5 Inner string cementing
For large diameter casing, such as conductors and surface casing, conventional cementing techniques result in:

- The potential for cement contamination during pumping and displacement
- The use of large cement plugs which can get stuck in the casing
- Large displacement volumes
- Long pumping times
- Large volume of cement left inside the casing between float collar and shoe.

An alternative technique, known as a stinger cement job, is to cement the casing through a tubing or drillpipe string, known as a cement stinger, rather than through the casing itself.

In the case of a stinger cement job the casing is run as before, but with a special float shoe (Figure 15) rather than the conventional shoe and float collar. A special sealing adapter, which can seal in the seal bore of the seal float shoe, is attached to the cement stinger. Once the casing has been run, the cementing string (generally tubing or drillpipe), with the seal adapter attached, is run and stabbed into the float shoe. Drilling mud is then circulated around the system to ensure that the stinger and annulus are clear of any debris. The cement slurry is then pumped with liquid spacers ahead and behind the cement slurry. No plugs are used in this type of cementing operation since the diameter of the stinger is generally so small that contamination of the cement is unlikely if a large enough liquid spacer is used. The cement slurry is generally under-displaced so that when the seal adapter on the stinger is pulled from the shoe the excess cement falls down on top of the shoe. This can be subsequently drilled out when the next hole section is being drilled. Under-displacement however ensures that the cement slurry is not displaced up above the casing shoe, leaving spacer and drilling mud across the shoe. After the cement has been displaced, and the float has been checked for backflow, the cement stinger can be retrieved. This method is suitable for casing diameters of 13 3/8” and larger. The main disadvantage of this method is that for long casing strings rig time is lost in running and retrieving the inner string.
4.6 Liner cementing
Liners are run on drillpipe and therefore the conventional cementing techniques cannot be used for cementing a liner. Special equipment must be used for cementing these liners.

As with a full string of casing the liner has a float collar and shoe installed. In addition there is a landing collar, positioned about two joints above the float collar (Figure 16). A wiper plug is held on the end of the tailpipe of the running string by shear pins.
The liner is run on drillpipe and the hanger is set at the correct point inside the previous casing string. Mud is circulated to ensure that the liner and the annulus is free from debris, and to condition the mud. Before the cementing operation begins the liner setting tool is backed off to ensure that it can be recovered at the end of the cement job. The cementing procedure is as follows:

1. Pump spacer ahead of cement slurry
2. Pump slurry
3. Release pump down plug
4. Displace cement down the running string and out of the liner into the annulus
5. Continue pumping until the pump down plug lands on the wiper plug.
6. Apply pressure to the pump down plug and shear out the pins on the wiper plug. This releases the wiper plug
7. Both plugs move down the liner until they latch onto landing collar
8. Bump the plugs with 1000 psi pressure
9. Bleed off pressure and check for back flow

Since there is no bottom plug in front of the slurry the wiper plug cleans off debris and mud from the inside of the liner. This material will contaminate the cement immediately ahead of the wiper plug. The spacing between the landing collar and the shoe should be adequate to accommodate this contaminated cement, and thus prevent it from reaching the annulus where it would create a poor cement job around the shoe.
To promote a good cement job, cement in excess of that required to fill the annulus between the liner and the borehole is used. This excess cement will pass up around the liner top and settle on top of the liner running assembly. Once the cement is in place the liner setting tool is quickly picked up out of the liner. With the tail pipe above the liner top the excess cement can be reverse circulated out. The setting tool can then be retrieved.

In practice it is very difficult to obtain a good cement job on a liner. The main reasons for this are:

(a) **Minimal annular clearances**
A 7" OD liner run in an 8 1/2" hole gives a clearance of only 3/4" (assuming the liner is perfectly centred). This small clearance means that:

- It is difficult to run the liner (surge pressure)
- High pressure drops occur during circulation (lost circulation problems)
- It is difficult to centralise the liner
- Cement placement is poor (channeling)

(b) **Mud contamination**
When the cement comes in contact with mud or mud cake it may develop high viscosity. The increased pump pressure required to move this contaminated cement up the annulus may cause formation breakdown. Fluid loss additives must be used to prevent dehydration of the cement which may cause bridging in the annulus.

(c) **Lack of pipe movement**
Due to risk of sticking the setting tool, most operators want to be free of the liner before cementing begins. By disconnecting the setting tool the liner cannot be moved during the cement job. This lack of movement reduces the efficiency of cement placement. Due to these problems it is often necessary to carry out a remedial squeeze job at the top of the liner (Figure 17). It is becoming more common these days to remain latched on top of the liner and rotate the liner whilst the cement is being displaced into position. A special piece of liner running equipment, known as a rotating liner assembly, is used for this purpose.
4.7 Recommendations for a good cement job

The main cause for poor isolation after a cement job is the presence of mud channels in the cement sheath in the annulus. These channels of gelled mud exist because the mud in the annulus has not been displaced by the cement slurry. This can occur for many reasons. The main reason for this is poor centralisation of the casing in the borehole, during the cementing operation. When mud is being displaced from the annulus the cement will follow the least path of resistance. If the pipe is not properly centralised the highest resistance to flow occurs where the clearance is least. This is where mud channels are most likely to occur (Figure 18).

In addition, field tests have shown that for a good cement bond to develop the formation should be in contact with the cement slurry for a certain time period while the cement is being displaced. The recommended contact time (pump past time) is about 10 minutes for most cement jobs. To improve mud displacement and obtain a good cement bond the following practices are recommended:

- Use centralisers, especially at critical points in the casing string

- Move the casing during the cement job. In general, rotation is preferred to reciprocation, since the latter may cause surging against the formation. A specially designed swivel may be installed between the cementing head and the casing to allow rotation. (Centralisers remain static and allow the casing to rotate within them.)

- Before doing the cement job, condition the mud (low PV, low YP) to ensure good flow properties, so that it can be easily displaced.
• Displace the spacer in turbulent flow. This may not be practicable in large
diameter casing where the high pump rates and pressures may cause erosion or
formation breakdown.

• Use spacers to prevent mud contamination in the annulus.

![Image](image.png)

*Figure 18* Effect of centralisation on channeling

5. **SQUEEZE CEMENTING**

Squeeze cementing is the process by which hydraulic pressure is used to force
cement slurry through holes in the casing and into the annulus and/or the formation.
Squeeze cement jobs are often used to carry out remedial operations during a
workover on the well (Figure 3). The main applications of squeeze cementing are:

• To seal off gas or water producing zones, and thus maximise oil production
  from the completion interval

• To repair casing failures by squeezing cement through leaking joints or
corrosion hole

• To seal off lost circulation zones

• To carry out remedial work on a poor primary cement job (e.g. to fill up the
  annulus)

• To prevent vertical reservoir fluid migration into producing zones (block
  squeeze)

• To prevent fluids escaping from abandoned zones.
During squeeze cementing the pores in the rock rarely allow whole cement to enter the formation since a permeability of about 500 darcies would be required for this to happen. There are two processes by which cement can be squeezed:

- High pressure squeeze - This technique requires that the formation be fractured, which then allows the cement slurry to be pumped into the fractured zone.

- Low pressure squeeze - During this technique the fracture gradient of the formation is not exceeded. Cement slurry is placed against the formation, and when pressure is applied the fluid content (filtrate) of the cement is squeezed into the rock, while the solid cement material (filter cake) builds up on the face of the formation.

5.1 High Pressure Squeeze
In a high pressure squeeze the formation is initially fractured (broken down) by a solids free breakdown fluid. A solids free fluid is used because a solids laden fluid such as drilling mud will build up a filter cake and prevent injection into the formation. Solids free fluids such as water or brine are recommended. The direction of the fracture depends on the rock stresses present in the formation. The fracture will occur along a plane perpendicular to the direction of the least compressive stress (Figure 19). In general, the vertical stress, due to the overburden, will be greater than the horizontal stresses. A vertical fracture is therefore more likely. In practice the fracture direction is difficult to predict since it may follow natural fractures in the formation. Since squeeze cementing is often used to isolate various horizontal zones a vertical fracture is of little use (vertical fluid movement is not prevented).
Effect of well depth and vertical-horizontal formation stresses on type of hydraulic fracture induced by injected fluid. Horizontal fracture pressure is less than overburden pressure, this is usually the case at depths greater than 3,000 feet.

\[ P_F > \sigma_v; \sigma_v < \sigma_{H1} \text{ or } \sigma_{H2} \]

\[ P_F > \sigma_{H1} \text{ or } \sigma_{H2}; \sigma_{H1} \text{ or } \sigma_{H2} < \sigma_v \]

Figure 19 Horizontal and vertical fracturing

After the formation is broken down a slurry of cement is spotted adjacent to the formation, and then pumped into the zone at a slow rate. The injection pressure should gradually build up as the cement fills up the fractured zone. After the cement has been squeezed the pressure is released to check for back flow. The disadvantages of this technique are:

- No control over the orientation of the fracture
- Large volumes of cement may be necessary to seal off the fracture
- Mud filled perforations may not be opened up by fracturing, so the cement may not seal them off effectively.

5.2 Low Pressure Squeeze

It is generally accepted that a low pressure squeeze is a more efficient method of sealing off unwanted perforated zones. In a low pressure squeeze the formation is not fractured. Instead a cement slurry is gently squeezed against the formation. A cement slurry consists of finely divided solids dispersed in a liquid. The solids are too large to be displaced into the formation. As pressure is applied, the liquid phase
is forced into the pores, leaving a deposit of solid material or filter cake behind. As the filter cake of dehydrated cement begins to build up, the impermeable barrier prevents further filtrate invasion. The filtrate must then be diverted to other parts of the perforated interval. This technique therefore creates an impermeable seal across the perforated zone. Fluid loss additives are important to perform this technique successfully. Neat cement has a high fluid loss, resulting in rapid dehydration which causes bridging before the other perforations are sealed off. Conversely a very low fluid loss means a slow filter cake build up and long cement placement time. Key factors which affect the build up of cement filter cake are:

- Fluid loss (generally 50 - 200 cc)
- Water to solids ratio (0.4 by weight)
- Formation characteristics (permeability, pore pressure)
- Squeeze pressure

Only a small volume of cement is required for a low pressure squeeze. Perforations must be free from mud or other plugging material. If the well has been producing for some time these perforations have to be washed out, sometimes with an acid solution. The general procedure for a low pressure squeeze job is:

1. Water is pumped into the zone to establish whether the formation can be squeezed (injectivity test). If water cannot be injected the squeeze job cannot be done without fracturing the formation
2. Spot the cement slurry at the required depth
3. Apply moderate squeeze pressure
4. Stop pumping and check for bleed off
5. Continue pumping until bleed off ceases for about 30 mins
6. Stop displacement of cement and hold pressure
7. Reverse circulate out excess cement from casing

A properly designed slurry will leave only a small cement node inside the casing after removing the excess cement. Throughout the procedure squeeze pressure is kept below the fracture gradient. A running squeeze is where the cement is pumped slowly and continuously until the final squeeze pressure is obtained. This is often used for repairing a primary cement job. A hesitation squeeze is where pumping is stopped at regular intervals to allow time for the slurry to dehydrate and form a filter cake. Small volumes of cement (1/4 - 1/2 bbl) are pumped each time separated by a delay of 10 - 15 mins. This technique is dangerous if the cement is still in contact with the drillpipe or packer.

5.3 Equipment Used for Squeeze Cementing
The high pressure and low pressure squeeze operations can be conducted with or without packers.

(a) Bradenhead squeeze
This technique involves pumping cement through drill pipe without the use of a packer (Figure 20). The cement is spotted at the required depth. The BOPs and the annulus are closed in and displacing fluid is pumped down, forcing the cement into the perforations, since it cannot move up the annulus. This is the simplest method of placing and squeezing cement, but has certain disadvantages:
• It is difficult to place the cement accurately against the target zone
• It cannot be used for squeezing off one set of perforations if other perforations are to remain open
• Casing is pressured up, and so squeeze pressure is limited by burst resistance

A Bradenhead squeeze is only generally used for a low-pressure squeeze job.

Schematic of Bradenhead squeeze technique normally used on low pressure formations.

Cement is circulated into place down drill pipe (left), then the wellhead, or BOP, is closed (centre) and squeeze pressure is applied. Reverse circulating through perforations removes excess cement, or the plug can be drilled out.

**Figure 20** Bradenhead technique

(b) Squeeze using a packer
The use of a packer makes it possible to place the cement more accurately, and apply higher squeeze pressures. The packer seals off the annulus, but allows communication between drill pipe and the wellbore beneath the packer. (Figure 21)
Two types of packer may be used in this type of operation:

(i) Drillable packer (cement retainer)
This type of packer contains a back pressure valve which will prevent the cement flowing back after the squeeze. These are mainly used for remedial work on primary cement jobs, or to close off water producing zones. The packer is run on drill pipe or wireline and set just above or between sets of perforations. When the cement has been squeezed successfully the drill pipe can be removed, closing the back pressure valve. The advantages of these packers are:

• Good depth control
• Back pressure valve prevents cement back flowing
• Drill pipe recovered without disturbing cement

The major disadvantage is that they can only be used once then drilled out.

(ii)Retrievable packer (cement retainer)
These can be set and released many times on one trip. This makes them suitable for repairing a series of casing leaks or selectively squeezing off sets of perforations. By-pass ports in the packer allow annular communication, but these ports are closed during the squeeze job. When the packer is released there may be some backflow, and the cement filter cake may be disturbed. If this happens the packer should be re-set and the squeeze pressure applied until the cement sets.

The basic procedure for squeezing with a retrieveable packer is:

1. run the packer on drillpipe and set it at required depth with by-pass open
2. pump the cement slurry (keep back pressure on annulus to prevent cement falling

The packer setting depth should be considered carefully. If positioned too high above the perforations the slurry will be contaminated by the wellbore fluids and large volumes of fluid from below the packer will be pumped into the formation.
ahead of the cement. If the packer is set too low it may become stuck in the cement. Generally the packer is set 30 - 50 ft above the perforations.

Sometimes a tail pipe is used below the packer to ensure that only cement is squeezed into the perforations, and there is less chance of getting stuck (Figure 21). **Bridge plugs** are often set in the wellbore, to isolate zones which are not to be treated. They seal off the entire wellbore, and hold pressure from above and below. Bridge plugs can either be drillable or retrievable.

![Figure 22 Balanced Plug Cementation](image)

**5.4 Testing the Squeeze Job**

After the cement has hardened it must be pressure tested. The tests should include both positive and negative differential pressure. The following should be considered when making a test:

- A positive pressure test can be performed by closing the BOPs and pressuring up on the casing. (Do not exceed formation fracture gradient.)

- A negative pressure test (or **inflow test**) can be performed by reducing the hydrostatic pressure inside the casing. This can be done using a DST tool or displacing with the well to diesel. This test is more meaningful since mud filled perforations may hold pressure from the casing, but may become unblocked when pressure from the formation is applied.
Figure 23 Dump Bailer Plug Cementation

6. CEMENT PLUGS

At some stage during the life of a well a cement plug may have to be placed in the wellbore. A cement plug is designed to fill a length of casing or open hole to prevent vertical fluid movement. Cement plugs may be used for:

- Abandoning depleted zones
- Seal off lost circulation zones
- Providing a kick off point for directional drilling (e.g., side-tracking around fish)
- Isolating a zone for formation testing
- Abandoning an entire well (government regulations usually insist on leaving a series of cement plugs in the well prior to moving off location).

The major problem when setting cement plugs is avoiding mud contamination during placement of the cement. Certain precautions should be taken to reduce contamination.

- Select a section of clean hole which is in gauge, and calculate the volume required (add on a certain amount of excess). The plug should be long enough to allow for some contamination (500’ plugs are common). The top of the plug should be 250’ above the productive zone
- Condition the mud prior to placing the plug
- Use a preflush fluid ahead of the cement
- Use densified cement slurry (i.e., less mixwater than normal)
After the cement has hardened the final position of the plug should be checked by running in and tagging the cement. There are three commonly used techniques for placing a cement plug:

(a) Balanced plug (Figure 22)
This method is aimed at achieving an equal level of cement in the drillpipe and annulus. Preflush, cement slurry and spacer fluid are pumped down the drillpipe and displaced with mud. The displacement continues until the level of cement inside and outside the drillpipe is the same (hence balanced). If the levels are not the same then a U-tube effect will take pace. The drillpipe can then be retrieved leaving the plug in place.

(b) Dump bailer (Figure 23)
A dump bailer is an electrically operated device which is run on wireline. A permanent bridge plug is set below the required plug back depth. A cement bailer containing the slurry is then lowered down the well on wireline. When the bailer reaches the bridge plug the slurry is released and sits on top of the bridge plug. The advantages of this method are:

- High accuracy of depth control
- Reduced risk of contamination of the cement

the disadvantages are:

- Only a small volume of cement can be dumped at a time - several runs may be necessary
- It is not suitable for deep wells, unless retarders used.

7. EVALUATION OF CEMENT JOBS

A primary cement job can be considered a failure if the cement does not isolate undesirable zones. This will occur if:

- The cement does not fill the annulus to the required height between the casing and the borehole.

- The cement does not provide a good seal between the casing and borehole and fluids leak through the cement sheath to surface.

- The cement does not provide a good seal at the casing shoe and a poor leak off test is achieved

When any such failures occur some remedial work must be carried out. A number of methods can be used to assess the effectiveness of the cement job. These include:
Figure 24 Estimating top of cement in annulus by running a temperature log

Figure 25 Estimating top of cement by running radioactivity log
Detecting Top of Cement (TOC)

(a) Temperature surveys (Figure 24)
This involves running a thermometer inside the casing just after the cement job. The thermometer responds to the heat generated by the cement hydration, and so can be used to detect the top of the cement column in the annulus.

(b) Radioactive surveys (Figure 25)
Radioactive tracers can be added to the cement slurry before it is pumped (Carnolite is commonly used). A logging tool is then run when the cement job is complete. This tool detects the top of the cement in the annulus, by identifying where the radioactivity decreases to the background natural radioactivity of the formation.

Detecting Top of Cement (TOC) and the Measuring the Quality of the Cement Bond

(a) Cement bond logs (CBL)
The cement bond logging tools have become the standard method of evaluating cement jobs since they not only detect the top of cement, but also indicate how good the cement bond is. The CBL tool is basically a sonic tool which is run on wireline. The distance between transmitter and receiver is about 3 ft (Figure 26). The logging tool must be centralised in the hole to give accurate results. Both the time taken for the signal to reach the receiver, and the amplitude of the returning signal, give an indication of the cement bond. Since the speed of sound is greater in casing than in the formation or mud the first signals which are received at the receiver are those which travelled through the casing (Figure 27). If the amplitude (E₁) is large (strong signal) this indicates that the pipe is free (poor bond). When cement is firmly bonded to the casing and the formation the signal is attenuated, and is characteristic of the formation behind the casing.

![Figure 26 Schematic of CBL tool](image-url)
(b) the Variable Density Log (VDL)

The CBL log usually gives an amplitude curve and provides an indication of the quality of the bond between the casing and cement. A VDL (variable density log), provides the wavetrain of the received signal (Figure 28), and can indicate the quality of the cement bond between the casing and cement, and the cement and the formation. The signals which pass directly through the casing show up as parallel, straight lines to the left of the VDL plot. A good bond between the casing and cement and cement and formation is shown by wavy lines to the right of the VDL plot. The wavy lines correspond to those signals which have passed into and through the formation before passing back through the cement sheath and casing to the receiver. If the bonding is poor the signals will not reach the formation and parallel lines will be recorded all across the VDL plot.

The interpretation of CBL logs is still controversial. There is no standard API scale to measure the effectiveness of the cement bond. There are many factors which can lead to false interpretation:

- During the setting process the velocity and amplitude of the signals varies significantly. It is recommended that the CBL log is not run until 24 - 36 hours after the cement job to give realistic results.
- Cement composition affects signal transmission
- The thickness of the cement sheath will cause changes in the attenuation of the signal
- The CBL will react to the presence of a microannulus (a small gap between casing and cement). The microannulus usually heals with time and is not a critical factor. Some operators recommend running the CBL under pressure to eliminate the microannulus effect

![Figure 27 Signals picked up by receiver](image-url)
The following calculations must be undertaken prior to a cementation operation:

- Slurry Requirements
- No. of sacks of Cement
- Volume of Mixwater
- Volume of Additives
- Displacement Volume Duration of Operation
These calculations will form the basis of the cementing programme. They should be performed in this sequence as will be seen below.

1. Cement Slurry Requirements:
Sufficient cement slurry must be mixed and pumped to fill up the following (see Fig 29):

A - the annular space between the casing and the borehole wall,
B - the annular space between the casings (in the case of a two stage cementation operation)
C - the openhole below the casing (rathole)
D - the shoetrack

The volume of slurry that is required will dictate the amount of dry cement, mixwater and additives that will be required for the operation.

![Figure 29 Single Stage Cementing Operation](image)

In addition to the calculated volumes an excess of slurry will generally be mixed and pumped to accommodate any errors in the calculated volumes. These errors may arise due to inaccuracies in the size of the borehole (due to washouts etc.). It is common to mix an extra 10-20% of the calculated openhole volumes to accommodate these inaccuracies.

The volumetric capacities (quoted in bbls/linear ft or cuft/linear ft or m³/m) of the annuli, casings, and open hole are available from service company cementing tables. These volumetric capacities can be calculated directly but the cementing tables are simple to use and include a more accurate assessment of the displacement of the casing for instance and the capacities based on nominal diameters.

In the case of a two stage operation (Figure 30) the volume of slurry used in the first stage of the operation is the same as that for a single stage operation. The second stage slurry volume is the slurry required to fill the annulus between the casing and hole (or casing/casing if the multi-stage collar is inside the previous shoe) annular space.
2. **Number of Sacks of Cement**

Although cement and other dry chemicals are delivered to the rigsite in bulk tanks, the amount of dry cement powder is generally quoted in terms of the number of sacks (sxs) of cement required. Each sack of cement is equivalent to 1 cu. ft of cement.

The number of sacks of cement required for the cement operation will depend on the amount of slurry required for the operation (calculated above) and the amount of cement slurry that can be produced from a sack of cement. The amount of cement slurry that can be produced from a sack of cement, known as the yield of the cement, will depend on the type of cement powder (API classification) and the amount of mixwater mixed with the cement powder. The latter will also depend on the type of cement and will vary with pressure and temperature. The number of sacks of cement required for the operation can be calculated from the following:

\[
\text{No. of Sacks} = \frac{\text{Total Volume of Slurry}}{\text{Yield of Cement}}
\]

3. **Mixwater Requirements**

The mixwater required to hydrate the cement powder will be prepared and stored in specially cleaned mud tanks. The amount of mixwater required for the operation will depend on the type of cement powder used. The volume of mixwater required for the cement slurry can be calculated from:

\[
\text{Mixwater Vol.} = \text{Mixwater per sack} \times \text{No. sxs}
\]

4. **Additive Requirements**

There are a variety of additives which may be added to cement. These additives may be delivered to the rigsite as liquid or dry additives. The amount of additive is generally quoted as a percentage of the cement powder used. Since each sack of cement weighs 94 lbs, the amount of additive can be quoted in weight (lbs) rather than volume. This can then be related to the number of sacks of additive. The number of sacks of additive can be calculated from:
Number of sacks of additive = No. sxs Cement x % Additive

Weight of additive = No. sxs of Additive x 94(lb/sk)

The amount of additive is always based on the volume of cement to be used.

5. Displacement Volume

The volume of mud used to displace the cement from the cement stinger or the casing during the cementing operation is commonly known as the displacement volume. The displacement volume is dependant on the way in which the operation is conducted.

a. Stinger Operation:
The displacement volume can be calculated from the volumetric capacity of the cement stinger and the depth of the casing shoe. The cement is generally under displaced by 1-2 bbls of liquid.

Displacement Vol. = Volumetric capacity of stinger x Depth of Casing - 1bbl

b. Conventional Operation:
In a conventional cementing operation the displacement volume is calculated from the volumetric capacity of the casing and the depth of the float collar in the casing.

Displacement Vol. = Volumetric Capacity of Casing x Depth of Float Collar

c. Two-stage Cementing Operation:
In a two stage operation the first stage is firstly displaced by a volume of mud, calculated in the same way as a single stage cement operation described above. The second stage displacement is then calculated on the basis of the volumetric capacity of the casing and the depth of the second stage collar.

1st Stage:
Displacement Vol. = Volumetric Capacity of Casing x Depth of Float Collar

2nd stage:
Displacement Vol. = Volumetric Capacity of Casing x Depth of Multi-stage collar

The amount of mud to be pumped during the displacement operation may be quoted in terms of a volume (bbls, cuft etc.) or in terms of the number of strokes of the mud pump required to pump the mud volume. It will therefore be necessary to determine the volume of fluid pumped with each stoke of the pumps (vol./stroke). The number of strokes required to displace the cement will therefore be calculated from:

Number of strokes = Volume of displacement fluid/Vol. of fluid per stroke
6. Duration of Operation

The duration of the operation will be used to determine the required setting time for the cement formulation. The duration of the operation will be calculated on the basis of the mixing rate for the cement, the pumping rate for the cement slurry and the pumping rate for the displacing mud. An additional period of time, known as a contingency time, is added to the calculated duration to account for any operational problems during the operation. This contingency is generally 1 hour in duration.

The duration of the operation can be calculated from:

\[
\text{Duration} = \frac{\text{Vol. of Slurry}}{\text{Mixing Rate}} + \frac{\text{Vol. of Slurry}}{\text{Pumping Rate}} + \frac{\text{Displacement Vol.}}{\text{Displacement Rate}} + \text{Contingency Time (1hr.)}
\]

EXAMPLE OF CEMENT VOLUME CALCULATIONS

The 9 5/8” Casing of a well is to be cemented in place with a single stage cementing operation. The appropriate calculations are to be conducted prior to the operation. The details of the operation are as follows:

- 9 5/8” casing set at: 13800’,
- 12 1/4” hole: 13810’
- 13 3/8” 68 lb/ft casing set at: 6200’
- TOC outside 9 5/8” casing: 3000’ above shoe
- Assume gauge hole, add 20% excess in open hole

The casing is to be cemented with class G cement with the following additives:

- 0.2% D13R (retarder)
- 1% D65 (friction reducer)
- Slurry density = 15.9 ppg

![Figure 31 Example of Cementing Calculation](image-url)
1. Slurry Volume Between The Casing and Hole:

9 5/8" csg/ 12 1/4" hole capacity = 0.3132 ft³/ft
annular volume = 3000 x 0.3132 = 939.6 ft³
plus 20% excess = 187.9 ft³
= 1127.5 ft³ => 1128 ft³

2. Slurry Volume Below The Float Collar:

Cap. of 9 5/8, 47 lb/ft csg = 0.4110 ft³/ft
shoetrack vol. = 60 x 0.411
Total = 25 ft³

3. Slurry volume in the rathole

Cap. of 12 1/4" hole = 0.8185 ft³/ft
rathole vol. = 10 x 0.8185 = 8.2 ft³
plus 20% = 1.6 ft³
Total = 9.8 ft³ => 10 ft³

Total cement slurry vol. = 1128 + 25 + 10 = 1163 ft³

4. Amount of cement and mixwater

Yield of class G cement for density of 15.9 ppg = 1.14 ft³/sk
mixwater requirements = 4.96 gal/sk

No. of sks of cement = \( \frac{1163}{1.14} \) = 1020 sk
Mixwater required = 1020 x 4.96 gal = 5059 gal = 120 bbls

5. Amount of Additives:

Retarder D13R (0.2% by weight) = \( \frac{0.02 \times 1020 \times 94}{100} \) = 192 lb

Friction reducer (1.0% D65 by weight) = \( \frac{1 \times 1020 \times 94}{100} \) = 959 lb
6. Displacement Volume:

Displacement vol. = vol between cement head and float collar
= 0.4110 x 13740 = 5647 ft³ = 1006 bbl

(add 2 bbl for surface line)
= 1008 bbl

For Nat. pump 12-P-160, 7" liner 97% eff, 0.138 bbl/stk

No. of strokes = \frac{1008}{0.138} = 7300 strokes

EXERCISE 1 Cementing Calculations - Stinger Cementation

The 0" casing of a well is to be cemented to surface with class ‘C’ high early strength cement + 6% Bentonite using a stinger type cementation technique. Calculate the following for the 0" casing cementation:

a. The number of sacks of cement required (allow 100% excess in open hole).

b. The volume of mixwater required.

c. An estimate of the time taken to carry out the job. (Note: use an average mixing/pumping time of 5 bbls/min.)

EXERCISE 2 Cementing Calculations - Two Stage Cementation

The 13 3/8" casing string of a well is to be cemented using class ‘G’ cement. Calculate the following:

a. The required number of sacks of cement for a 1st stage of 700 ft. and a 2nd stage of 500 ft. (Allow 20% excess in open hole)

b. The volume of mixwater required for each stage.

c. The total hydrostatic pressure exerted at the bottom of each stage of cement (assume a 10 ppg mud is in the well when cementing).
d. The displacement volume for each stage.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Depth</th>
<th>Volume (ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20&quot; Casing shoe</td>
<td>0 - 1500 ft</td>
<td>1500 ft</td>
</tr>
<tr>
<td>13 3/8&quot; Casing</td>
<td>0 - 1000 ft</td>
<td>1000 ft</td>
</tr>
<tr>
<td>13 3/8&quot; Casing</td>
<td>1000 - 7000 ft</td>
<td>7000 ft</td>
</tr>
<tr>
<td>17 1/2&quot; open hole Depth</td>
<td>7030 ft</td>
<td></td>
</tr>
<tr>
<td>Stage Collar Depth</td>
<td>1500 ft</td>
<td></td>
</tr>
<tr>
<td>Shoetrack</td>
<td>60 ft</td>
<td></td>
</tr>
</tbody>
</table>

Cement stage 1 (7000-6300 ft.)
- **Class ‘G’**
- **Density:** 15.9 ppg
- **Yield:** 1.18 ft³/sk
- **Mixwater Requirements:** 0.67 ft³/sk

Cement stage 2 (1500-1000 ft.)
- **Class ‘G’ + 8% bentonite**
- **Density:** 13.3 ppg
- **Yield:** 1.89 ft³/sk
- **Mixwater Requirements:** 1.37 ft³/sk

**VOLUMETRIC CAPACITIES**

<table>
<thead>
<tr>
<th>Component</th>
<th>bbls/ft</th>
<th>ft³/ft</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drillpipe</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5&quot; drillpipe</td>
<td>0.01776</td>
<td>0.0997</td>
</tr>
<tr>
<td><strong>Casing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 3/8&quot; 72 lb/ft</td>
<td>0.1480</td>
<td>0.8314</td>
</tr>
<tr>
<td>13 3/8&quot; 77 lb/ft</td>
<td>0.1463</td>
<td>0.8215</td>
</tr>
<tr>
<td><strong>Open Hole</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26&quot; Hole</td>
<td>0.6566</td>
<td>3.687</td>
</tr>
<tr>
<td>17 1/2&quot; Hole</td>
<td>0.2975</td>
<td>1.6703</td>
</tr>
<tr>
<td><strong>Annular Spaces</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26&quot; hole x 20&quot; Casing</td>
<td>0.2681</td>
<td>1.5053</td>
</tr>
<tr>
<td>17 1/2&quot; hole x 13 3/8&quot; Casing</td>
<td>0.1237</td>
<td>0.6946</td>
</tr>
<tr>
<td>30&quot; Casing x 20&quot; Casing</td>
<td>0.3730</td>
<td>2.0944</td>
</tr>
<tr>
<td>20&quot; Casing x 13 3/8&quot; Casing</td>
<td>0.1816</td>
<td>1.0194</td>
</tr>
</tbody>
</table>
SOLUTION TO EXERCISES

Exercise 1  Cementing Calculations - Stinger Cementation

The surface (20") casing of a well is normally cemented to surface (continue pumping cement until it is seen at surface). In order to determine the volume of slurry required one calculates the annular space between the conductor (30") and the surface string (20") and between the surface string and the openhole. The volume of rathole is added to the above and the slurry volume is translated via the yield of the cement recipe to the number of sacks of cement required for the entire job.

The volume of mixwater required is specified in the slurry recipe in terms of cu ft. per sack of cement and will be determined on the basis of a required cement strength, setting time and allowable free water content.

The time required for the cement job will include the mixing and pumping time (assuming that the slurry is not batch mixed), the time to displace the cement from the cement stinger (since this type of job would normally be carried out using a stinger cementation technique) and 1 hr. contingency time to allow for operational problems during the job. The operation duration will be used to design the slurry so that the cement is set as soon as possible after the job is complete.

![Diagram]

a. No. sxs cement

Slurry volume between the 20" casing and 30" casing:

\[
\text{annular volume} = \frac{20" \text{ casing/30" casing capacity}}{2.0944 \text{ ft}^3/\text{ft}} = 400 \times 2.0944 = 838 \text{ ft}^3
\]

Slurry volume between the casing and hole:

\[
\text{annular volume} = \frac{20" \text{ csg/26" hole capacity}}{1.5053 \text{ ft}^3/\text{ft}} = 1100 \times 1.5053 = 1656 \text{ ft}^3
\]

plus 100% excess

\[
\text{Total} = 1656 \text{ ft}^3
\]
Slurry volume in the rathole

Cap. of 26" hole = 3.687 ft³/ft
rathole vol. = 30 x 3.687
= 111 ft³

plus 100%
= 111 ft³
Total = 222 ft³

**TOTAL SLURRY VOL. :** = 4372 ft³

Yield of class C cement for density of 13.1 ppg = 1.88 ft³/sk

**TOTAL No. SXS CEMENT :** 4372/1.88 = 2326 sxs

b. Mixwater Requirements

Mixwater requirements for class C cement with 6% Bentonite = 1.36 ft³/sk

Mixwater required = 2326 x 1.36
= 3163 ft³

c. Displacement Time

Total Displacement time = Time to mix and pump cement + time to displace cement

Total Volume of Cement = 4372 ft³
= 779 bbl

Displacement vol. = vol to displace down drillpipe leaving 1 bbl under displaced

d.p. capacity = 0.01776 bbl/ft
Displacement to 1500 ft = 0.01776 x 1500
= 26.6 bbl

(underdisplace by 1 bbl ) = 25.6 bbl

Total Volume to mix and displace = 779 + 25.6 = 804.6 bbls

**Total time @ 5 bbl/min** = 804.6/5
= 160.9 = 2.7 hrs
Exercise 2  Cementation Calculations - Two Stage Cementation

a. No. sxs cement

Stage 1:

Slurry volume between the casing and hole:
13 3/8" csg/ 17 1/2" hole capacity
annular volume
plus20% excess
Total

Slurry volume below the float collar:
Cap. of 13 3/8, 72 lb/ft csg
shoetrack vol.
Total

Slurry volume in the rathole
Cap. of 17 1/2" hole
rathole vol.
plus 20%
Total

TOTAL SLURRY VOL. STAGE 1:  = 693 ft³

Yield of class G cement for density of 15.9 ppg  = 1.18 ft³/sk

TOTAL No. SXS CEMENT STAGE 1: 693/1.18 = 587 sxs
Stage 2:
20” csg/ 13 3/8” csg annular volume

\[
= 1.0194 \text{ ft}^3/\text{ft} \\
= 500 \times 1.0194 \\
= 508 \text{ ft}^3
\]

**TOTAL SLURRY VOL. STAGE 2:** 

\[
508 \text{ ft}^3
\]

Yield of class G cement for density of 13.2 ppg

\[
= 1.89 \text{ ft}^3/\text{sk}
\]

**TOTAL No. SXS CEMENT STAGE 2:**

\[
508/1.89 = 269 \text{ sxs}
\]

b. Mixwater Requirements

Stage 1:
mixwater requirements for class G cement for density of 15.9 ppg

\[
= 0.67 \text{ ft}^3/\text{sk}
\]

Mixwater required

\[
= 587 \times 0.67 \\
= 393 \text{ ft}^3
\]

Stage 2:
mixwater requirements for class G cement for density of 13.2 ppg

\[
= 1.37 \text{ ft}^3/\text{sk}
\]

Mixwater required

\[
= 270 \times 1.37 \\
= 370 \text{ ft}^3
\]

c. Hydrostatic Head

Stage 1:
Mud Hydrostatic (0 - 6300 ft) + Cement Hydrostatic (6300 - 7030 ft)

\[
= 6300 \times 10 \times 0.052 + 730 \times 15.9 \times 0.052 \\
= 3880 \text{ psi}
\]

Stage 2:
Mud Hydrostatic (0 - 1000 ft) + Cement Hydrostatic (1000 - 1500 ft)

\[
= 1000 \times 10 \times 0.052 + 500 \times 13.2 \times 0.052 \\
= 863 \text{ psi}
\]

A knowledge of the hydrostatic pressure exerted by the cement slurry when it is place will ensure that the formation fracture pressure will not be exceeded during the cement job.
d. Displacement Volumes

Stage 1:
Displacement vol. = vol between cement head and float collar
\[ = 0.1463 \times 1000 \text{ (77 lb/ft casing)} + 0.148 \times 5940 \text{ (72 lb/ft casing)} \]
\[ = 1025 \text{ bbl} \]
(add 2 bbl for surface line) \[ = 1027 \text{ bbl} \]

Stage 2:
Displacement vol. = vol between cement head and stage collar
\[ = 0.1463 \times 1000 \text{ (77 lb/ft casing)} + 0.148 \times 500 \text{ (72 lb/ft casing)} \]
\[ = 220 \text{ bbl} \]
(add 2 bbl for surface line) \[ = 222 \text{ bbl} \]