Wellbore Plugging and Abandonment

API RECOMMENDED PRACTICE 65-3
FIRST EDITION, JUNE 2021

American
Petroleum
Institute

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Foreword

This document was prepared with input from oil and gas operators, drilling contractors, service companies, and consultants. Guidance is provided to accomplish the following:

— permanently abandon wells;

— place wells on inactive status (temporary abandonment).

Permanent abandonment is performed when there is no further utility for a wellbore by sealing the wellbore against fluid migration.

A well is placed on inactive status when there are plans for future utility of the wellbore. Temporary abandonment is performed by sealing the wellbore for the anticipated time of inactivity.

The purpose of this document is to address wellbore plugging and abandonment practices. The primary goals are protection of useable water sources, isolation of hydrocarbon bearing or water injection intervals, prevent any leakage to the surface, and prevention of unintended cross flow. Topics discussed include cementing practices and the placement of well barriers. This document does not address regulatory requirements nor surface reclamation.

The content of this document is not all inclusive and not intended to alleviate the need for detailed information found in textbooks, manuals, technical papers, or other documents. The formulation, adoption, and publication of API standards are not intended to inhibit anyone from using any other practices. Research into the installation and evaluation of permanent abandonment well barriers are ongoing. As new materials, isolation methods, placement techniques, and evaluation methods emerge these should be effectively reviewed by the user prior to use.

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Should: As used in a standard, “should” denotes a recommendation or that which is advised but not required in order to conform to the standard.

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1 Scope

1.1 General Considerations

This document provides guidance for the design, placement, and verification of cement plugs in wells to be temporarily or permanently abandoned, as well as remediation and verification of annular barriers. Wells temporarily abandoned (suspended) are intended to be re-entered in the future. The placement of barriers may depend on whether the well is to be temporarily or permanently abandoned.

The information in this document is general in nature. Wellbore plugging and abandonment practices will vary with regulatory requirements, well type, and purpose. Sound engineering and operational practices should be applied to each wellbore plugging operation. Cement plug lengths are not considered in this document.

1.2 Well Construction and Abandonment Practices

This document assumes that generally accepted well construction practices were followed during the installation of the cemented casings.

As specified in API 65-2, properly designed casing strings cemented in place provide multiple barriers during well operations.

Abandonment barriers may include those placed:

— across any exposed casing/liner shoe;

— in open hole;

— above perforated intervals in cased hole;

— at points where casing has been removed;

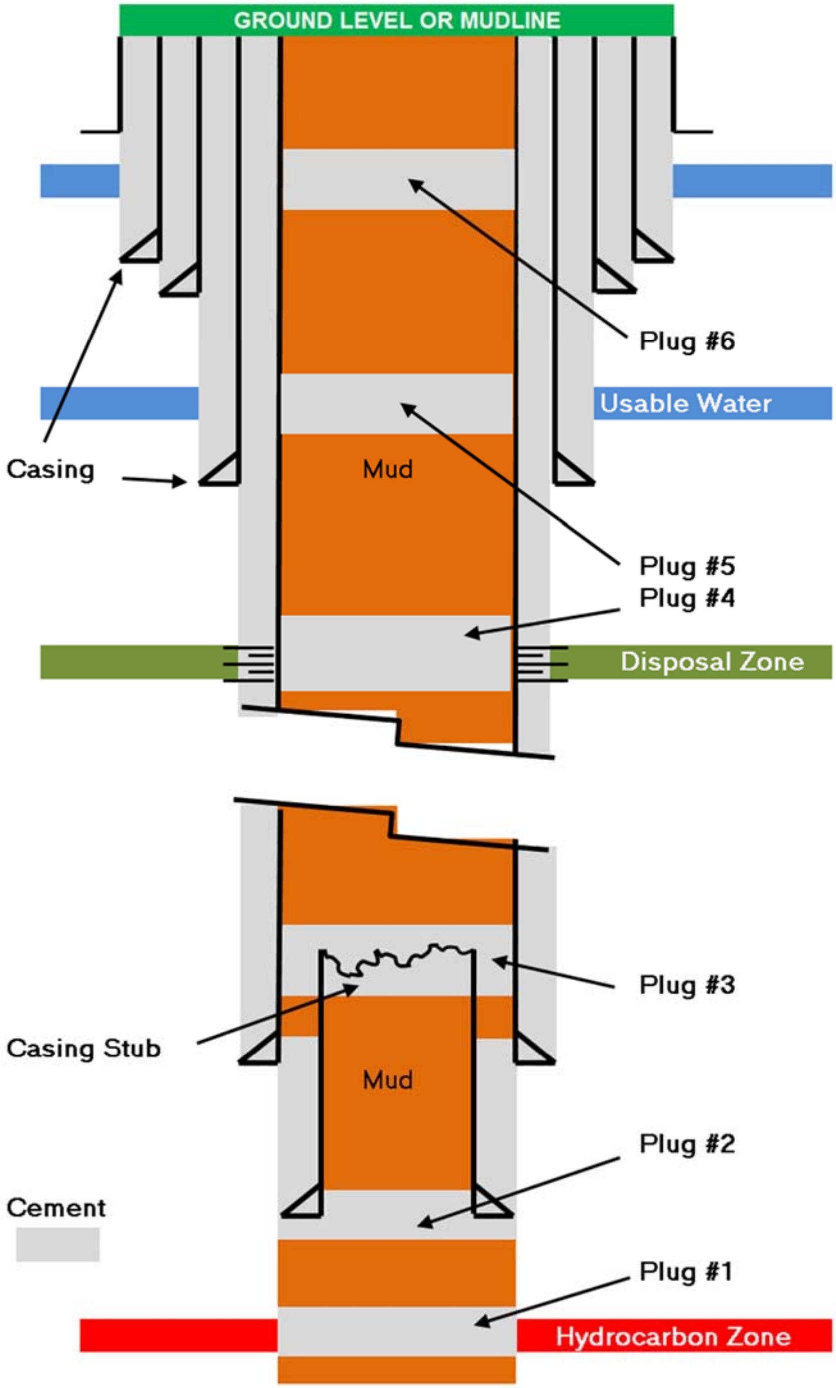
— across liner tops;

— above and below usable water sources;

— above or below hydrocarbon bearing zones or other potential flow zones;

— at the surface or mudline.

See Figure 1 for an example of a permanent well abandonment.



NOTE 1 Plug #1 may cover all open hole length in several cases.

NOTE 2 Plug #3 is commonly called a casing stub plug or “T” plug.

NOTE 3 Plug #6 is commonly called a surface or environmental plug.

NOTE 4 Top of cement in casing strings can vary depending on well construction.

Figure 1—Example Schematic of a Permanent Well Abandonment

2 Normative References

The following referenced document is indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document applies (including any amendments/addenda/errata).

API Standard 65-2, *Isolating Potential Flow Zones During Well Construction*

For a listing of other documents associated with this publication, refer to the Bibliography.

2.1 Use of SI and U.S. Customary Units

This document contains derived metric units (SI) and U.S. customary oilfield units. For the purposes of this document, the conversion between the systems is not exact and has been intentionally rounded to allow for ease of use in calibration and measurement.

3 Terms and Definitions, Symbols, and Abbreviations

3.1 Terms and Definitions

For the purposes of this document, the following terms and definitions apply.

3.1.1
barrier
A component or practice that, if properly installed, contributes to the total system reliability by preventing liquid or gas flow.

3.1.2
bridge plug
A mechanical device, usually equipped with elastomer elements, that acts as a temporary barrier.

NOTE 1 A pumpable sealant may be placed below it before being placed in the wellbore, or above it after being activated.

NOTE 2 It can be placed in the wellbore using a workstring, coiled tubing, or wireline.

3.1.3
cement
Any material or combination of materials fluidized and pumped into the well to provide a seal.

NOTE This includes pumpable sealants containing Portland cement, pozzolan blends, blast furnace slag blends, phosphate cement, hardening ceramics, resins, geo-polymers or other appropriate materials.

3.1.4
coiled tubing
A long, continuous length of pipe wound on a spool.

NOTE The pipe is straightened prior to pushing into a wellbore and rewound to coil the pipe back onto the storage spool pulling out of the wellbore.

3.1.5
dump bailer
A wireline or slickline tool used to place small volumes of cement in a wellbore.

3.1.6
inside blowout preventer
IBOP
A tool used as a check valve inside the workstring.

3.1.7
mud
Any wellbore fluid, including drilling fluids and completion fluids, containing organic or inorganic salts.

3.1.8
packer
A mechanical device, usually equipped with elastomer elements, placed in the well using a workstring, coiled tubing, or wireline to act as a barrier.

NOTE It may be either permanent or temporary/retrievable type.

3.1.9
plug
A verifiable barrier located within the wellbore that may be mechanical or cement.

3.1.10
retainer
A mechanical device, usually equipped with elastomer elements, that allows passage of fluid through a valve that can then be closed.

NOTE It can be placed in the wellbore using a workstring, coiled tubing, or wireline.

3.1.11
through-tubing
An intervention technique of running through an existing tubing string in the wellbore.

NOTE 1 Normally, a packer is deployed using this technique, enabling placement in a larger-diameter open hole or casing located below the existing tubing string.

NOTE 2 The packer is typically run on coiled tubing, wireline, or slickline.

3.1.12
workstring
A generic term used to describe a tubular that is used to convey a treatment or for well service activities.

NOTE Examples include jointed tubing, coiled tubing, or drill pipe.

3.2 Symbols and Abbreviations

3.2.1 Symbols

For the purpose of this document, symbols are only used for balanced plug calculations, they are provided under Annex A.

3.2.2 Abbreviations

For the purpose of this document, the following acronyms or abbreviations are used.

BHA bottom hole assembly

ECD equivalent circulating density

IBOP inside blowout preventer

NAF non-aqueous fluid

PWC perforation, wash, and cement

psi pound-force per square inch (lbf/in.^{2})

SCP sustained casing pressure

VRP viscous reactive pill

WOC waiting-on-cement

4 Applications and Operating Environment

4.1 Formation Types

4.1.1 Potential Flow Zones

Potential flow zones are any formations in a well where flow is possible when the wellbore pressure is less than the pore pressure (e.g., hydrocarbon zones, shallow gas, or overpressurized water zones that may be natural or induced). Isolation of these zones shall be the primary objective of wellbore plugging and abandonment unless cross flow is deemed acceptable. Prior to permanent abandonment operations, all potential flow zones in the wellbore shall be identified.

4.1.2 Usable Water Sources

Subsurface waters (aquifers) suitable for consumption by humans or animals with or without treatment are classified as usable water sources. These formation types shall be protected from contamination by fluid migration or surface water runoff.

4.1.3 Injection and Depleted Zones

Injection or disposal zones are geological formations whose strata are isolated from overlying usable water sources by an impermeable layer into which fluids are injected for disposal or charging. These formations may or may not be classified as depleted zones. Depleted zones are formations whose reservoir pressures are less than the adjacent formation pressures as a result of production operations. These zones may prevent plug stability during placement. Both injection and depleted zones shall be isolated during abandonment unless cross flow is deemed acceptable.

4.2 Positions

4.2.1 Barrier Installation

During the drilling of a well, the natural geologic seals to overpressured formations are penetrated by the wellbore. During well abandonment, the placement of a barrier prevents the flow of formation fluids to surface or seabed, cross flow between permeable formations, and contamination of usable water sources.

Since the initial geologic state was a continuous seal, well abandonment is typically performed by creating a continuous barrier across the wellbore at the natural seal location.

See Figure 2 for an illustration of a continuous barrier across the wellbore at the natural seal location.

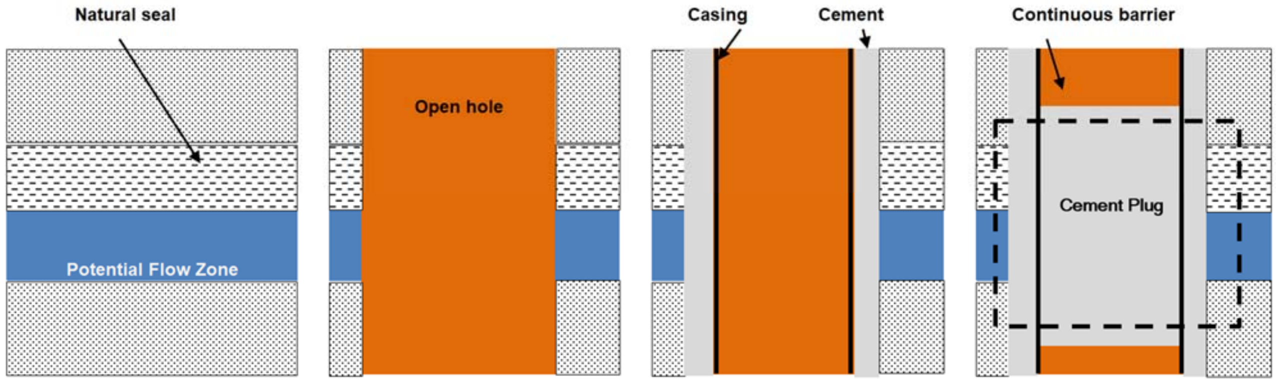


Figure 2—Illustration of a Continuous Barrier across the Wellbore at the Natural Seal Location

Permanent annular barriers set adjacent to the natural seal during the well construction phase can increase the efficiency of the permanent abandonment operations. During the construction of the well, considering field operational life can aide in the placement of barriers (e.g., conversion of a well to an injector, disposal).

During planning for permanent abandonment operations, potential flow zones identified during the well construction are reviewed and redefined if applicable. Local regulatory authorities may define zones that require permanent abandonment barriers.

The inclusion of a draft well abandonment plan or schematic showing the proposed locations of permanent barriers can aide in optimizing well construction activities in preparation for well abandonment.

4.2.2 Formation Pressures and Strengths

The location of a permanent abandonment barrier is typically at a depth where formation integrity can withstand the pressure from the potential flow zones being isolated. A natural seal for a potential flow zone typically starts immediately above the top of the potential flow zone. An understanding of individual seals to potential flow zones, and seals, which can contain all the pressures from above and below, can help plan the placement of permanent abandonment barriers.

The fluid gradient from each potential flow zone can be used in the determination of permanent abandonment barrier locations.

See Figure 3 for an example of the location of a permanent abandonment barrier placed at a depth where formation integrity (natural seal) can withstand the pressure from the potential flow zone being isolated.

Considerations for the placement of permanent abandonment barriers can include:

— location of potential flow zones and pore pressures;

— location of usable water sources;

— formation fracture pressure of natural seals;

— cross flow potential; direction and resultant equalized pressures;

— future field plans (e.g., injection activities);

— compaction, subsidence, and recharged formations;

— corrosion risks;

— field reservoir management requirements;

— regulatory requirements;

— location of natural faults and their ability to transmit fluids and/or pressure;

— ability to verify barrier;

— failure of a previous, temporary, or secondary barrier;

— operating environment.

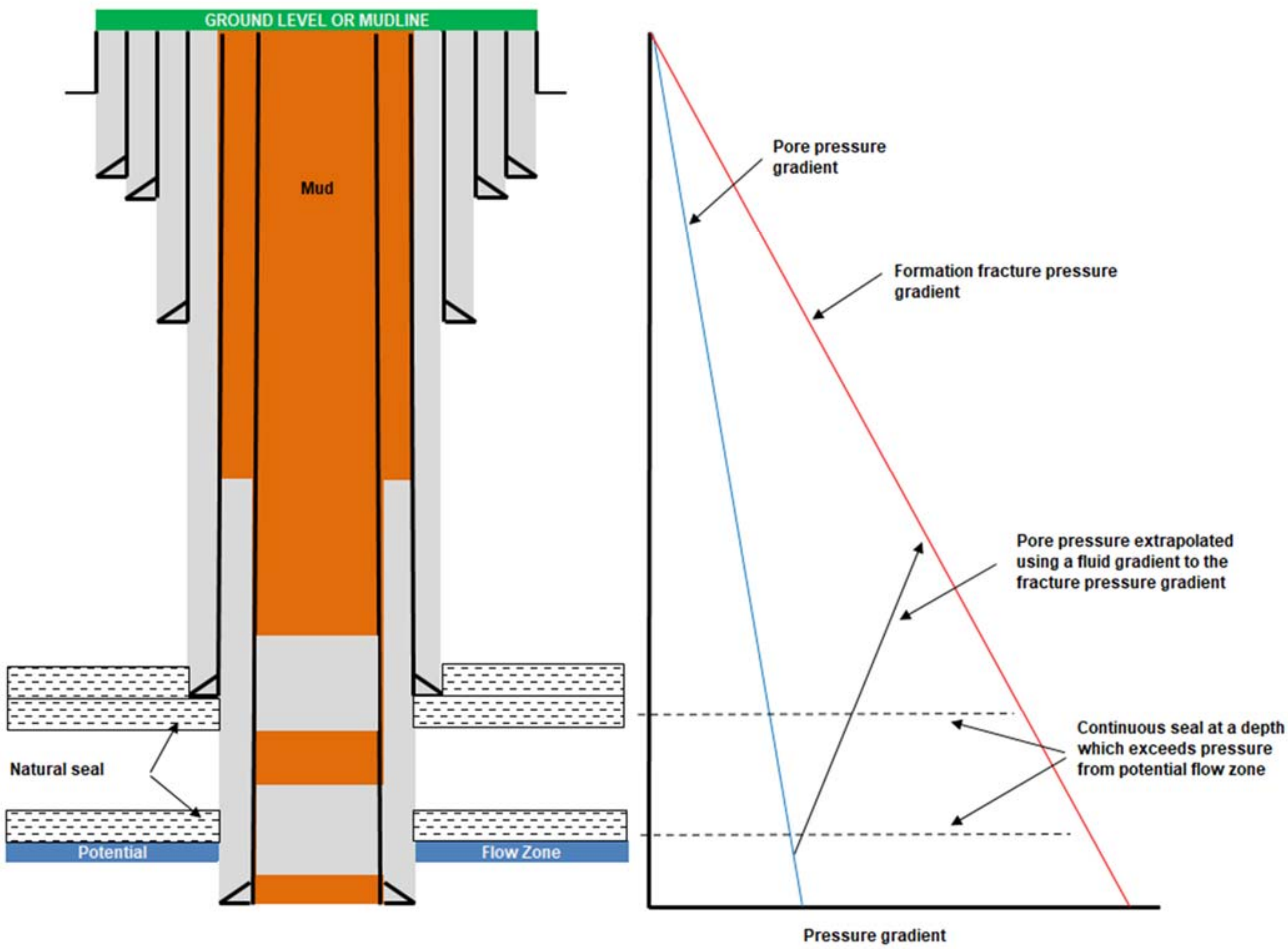


Figure 3—Two Continuous Barriers Adjacent to Natural Seals where Formation Integrity Exceeds Pressure from Potential Flow Zone

4.2.3 Open Hole

Methods used to place open hole abandonment plugs may include displacement, squeeze, coiled tubing, and through-tubing open hole inflatable packers.

Figure 4 shows a typical open hole abandonment using balanced plugs. Figure 5 shows a typical open hole abandonment using a cement retainer.

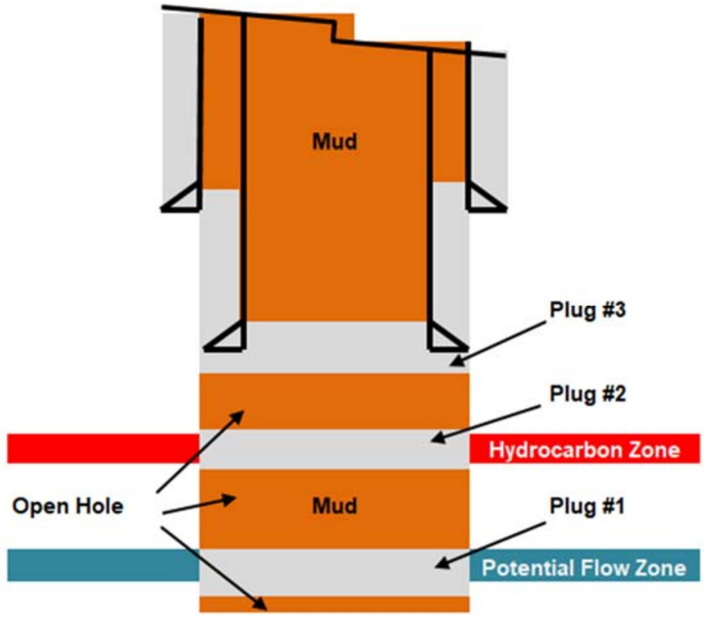


Figure 4—Open Hole Abandonment by Balanced Plugs

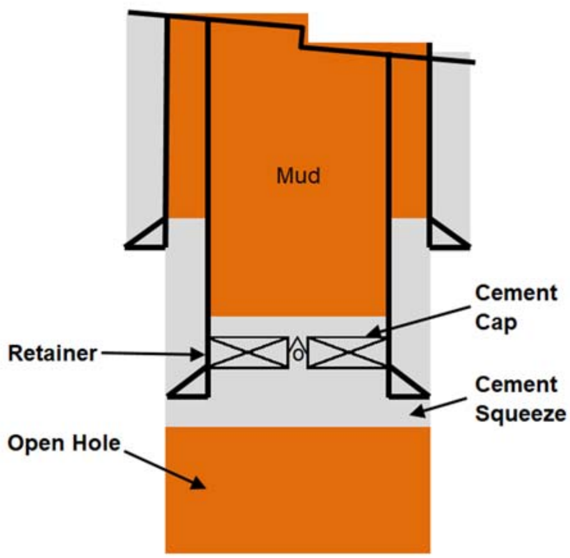


Figure 5—Open Hole Abandonment with a Cement Retainer Set at Casing Shoe

4.2.4 Cased Hole

Cased hole abandonments typically involve squeeze cementing and/or a cement plug to seal potential flow zone pathways, such as perforations, as well as placing cement plugs in the cased wellbore.

Figure 6 shows a typical cased hole abandonment using a perforation squeeze and a balanced plug. Figure 7 shows an example of a cased hole abandonment using a cement retainer for the same purpose.

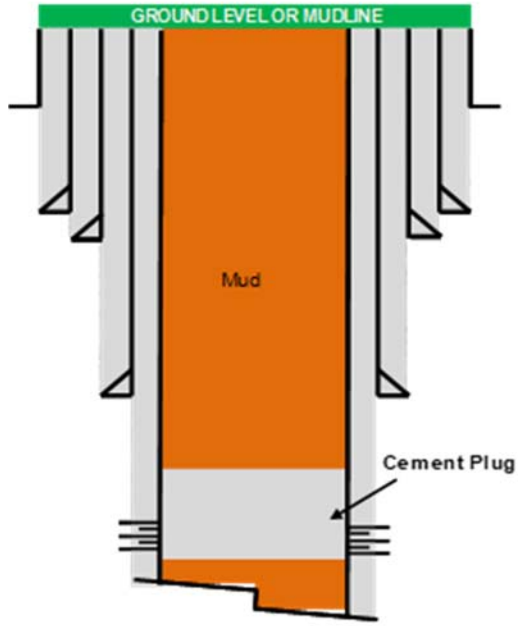


Figure 6—Cased Hole Abandonment with a Perforation Squeeze and a Balanced Plug

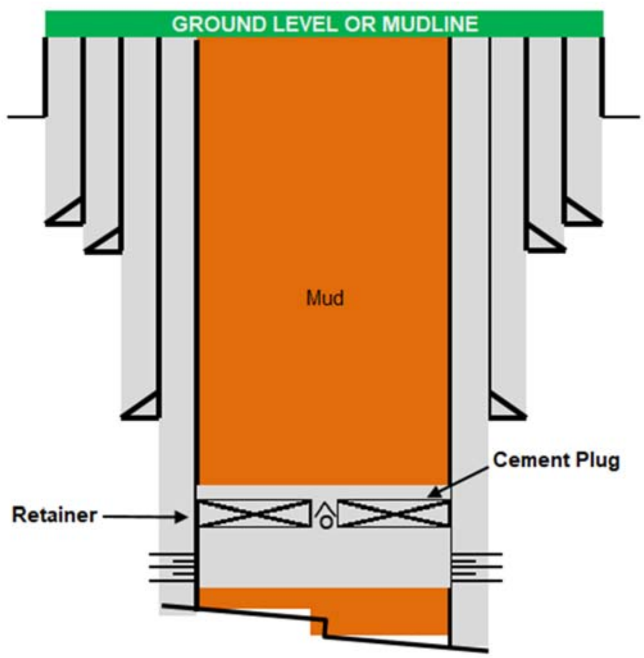


Figure 7—Cased Hole Abandonment with a Cement Retainer

4.2.5 Casing Shoe

The abandonment operations performed at the casing shoe provide a barrier to isolate the open hole below, and the open hole from the upper sections of the wellbore. Methods used to abandon a casing shoe may include displacement, squeeze, coiled tubing, and mechanical plugging.

Figure 8 shows an example of a cement plug used to isolate the open hole from the upper sections of the wellbore. Figure 9 shows an example of using a cement retainer to set a cement plug for the same purpose.

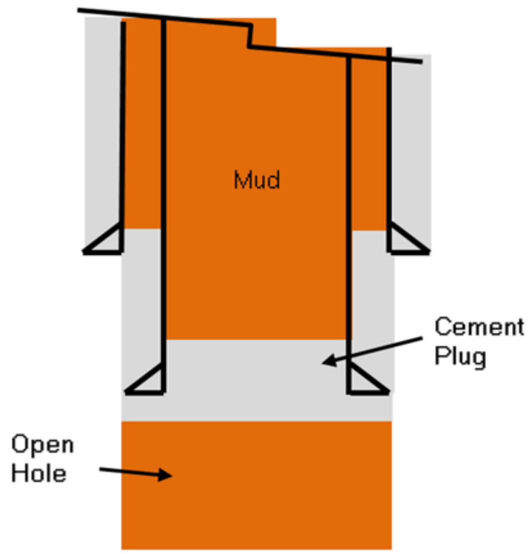


Figure 8—Casing Shoe Balanced Cement Plug

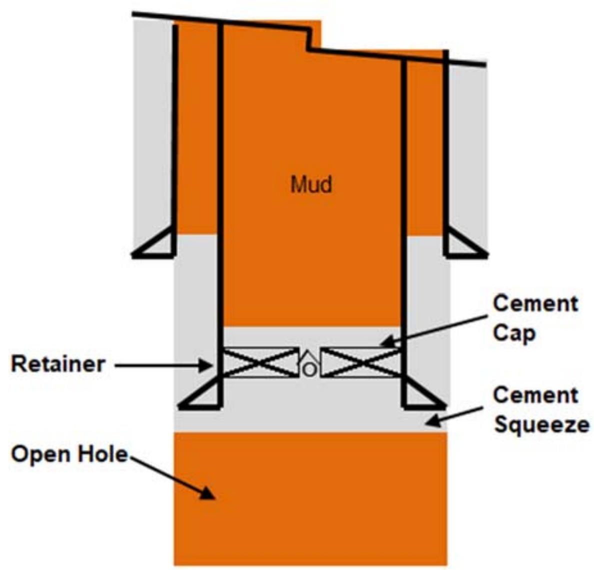


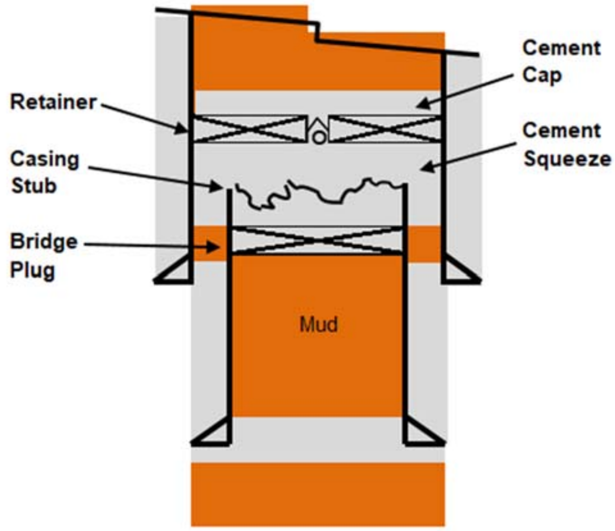
Figure 9—Casing Shoe Squeeze Cement Plug with Cement Retainer

4.2.6 Casing Stub or Liner Top

A casing stub or liner top can introduce a new flow path that was not isolated by wellbore barriers set deeper in the well. It may be required to place a plug across a casing stub or liner top to provide a barrier to isolate the sections of the wellbore below the casing stub or liner top from the upper sections of the wellbore.

Methods used to abandon a casing stub or liner top may include displacement, squeeze, coiled tubing, and mechanical plugging.

Figure 10 shows an example of a casing stub abandonment using a cement plug and a cement retainer. Figure 11 shows an example of a liner top abandonment.



NOTE A bridge plug may or may not be feasible for this type of abandonment.

Figure 10—Casing Stub Abandonment

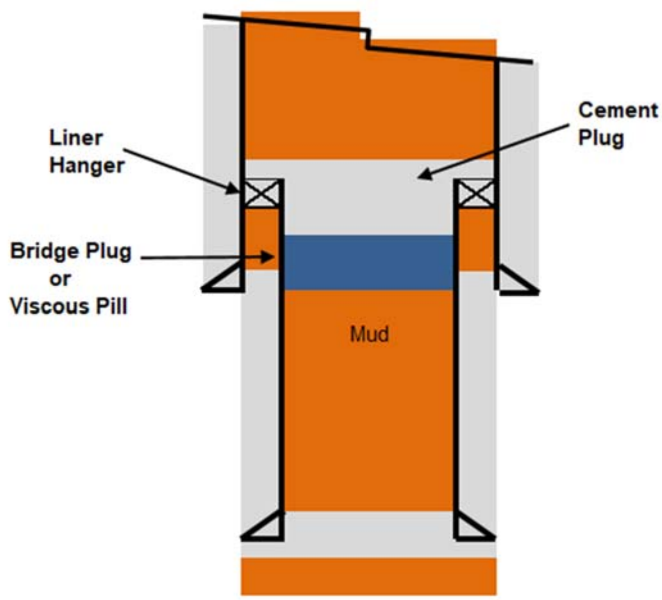


Figure 11—Liner Top Abandonment

4.2.7 Usable Water Sources

Cement plug(s) are typically placed across usable water sources or zones to completely isolate from wellbore contact above and below it. Methods used to isolate usable water sources may include the balanced plug displacement method, coiled tubing, and mechanical plugging.

Figure 12 shows an example of a balanced cement plug set inside the casing to isolate a usable water source.

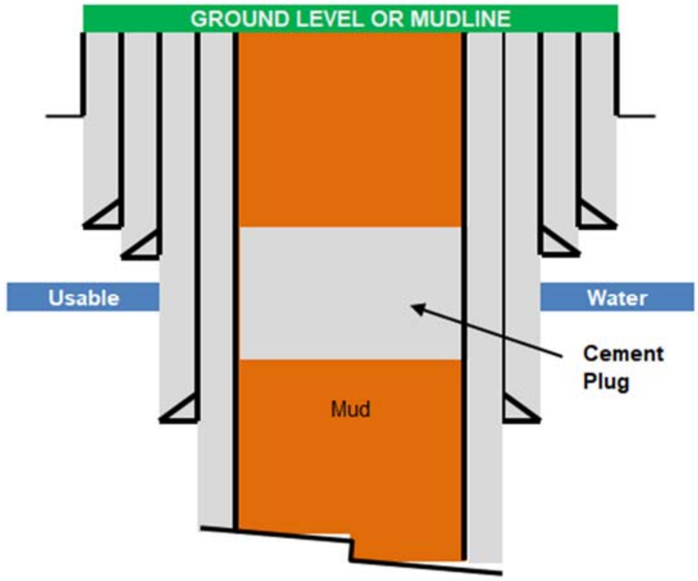


Figure 12—Balanced Cement Plug Inside Casing Across a Usable Water Source

4.2.8 Direct Access versus Subsea Wellheads

4.2.8.1 Direct Access

Direct access wellheads comprise all wells for which multiple casing annuli are accessible while operating the well. Also known as having a dry tree, this classification encompasses most onshore wells and those on offshore platforms. Several annuli on direct access wells can usually be continuously monitored for pressure. To facilitate abandonment, annuli that are not already fully cemented may allow circulation after perforating and be accessible for direct injection of kill fluids and cement.

4.2.8.2 Subsea Wellhead

Conventional subsea wellheads, located on the ocean floor, have all casing hangers and seal assemblies located inside the wellhead high-pressure housing, with each subsequent hanger landed above the previous casing as the well is drilled and casing strings are added. This design does not allow for access to any casing annuli while operating the well. A casing annulus on a subsea well can be accessed only during abandonment after the wellhead and production tubing have been removed, the casing string has been cut at some depth, and the casing hanger has been lifted from the high-pressure housing.

5 Material Consideration for Barriers

5.1 General

There are several materials available for consideration in the design of a barrier. Materials, in this document, can be classified as either chemical, natural, or mechanical-type. Each of these material classifications have limitations and/or boundaries that should be explored during the planning phase to evaluate the applicability of barrier material in the anticipated wellbore environment.

The materials compromising the barrier construction, whether stand-alone or part of a multi-component system, should have the following properties:

— inability for wellbore fluids to bypass in either direction whether through or across;

— no degradation of sealing capacity over time during the period of abandonment;

— avoidance of movement;

— appropriate for environment and application.

While it is not necessary, and, in fact, nearly impossible for a sealant to exhibit the same properties as the barrier or cap rock formation the sealant is generally placed across, the sealant should possess properties that allow it to function as a barrier.

If adequate information cannot be obtained from historical data, additional laboratory testing may be required to qualify existing or new materials for challenging chemical environments

Local regulations may stipulate material selection used for barriers. These regulatory requirements shall supersede any guidance provided in this document.

5.2 Environment

5.2.1 General

Wellbore environment shall be considered when selecting materials for barrier construction. The wellbore environment contains a set of operating conditions such as:

— temperature and pressure;

— chemical exposure;

— anticipated well events after placement.

5.2.2 Temperature and Pressure

The effect of temperature and pressure gradients across the planned barrier is an important design consideration when selecting materials for barrier construction. The selected material should provide the required properties to achieve successful placement in the well and long-term sealing properties required for well abandonment.

5.2.3 Chemical Exposure

The barrier should be able to withstand the most likely chemical exposure. The chemistry of well fluids should be considered when selecting materials for barrier construction. Examples of these fluids may include carbon dioxide, produced fluids whether natural or comingled with stimulation chemicals, hydrogen sulfide, microorganisms, completion fluids, or any other potential contaminant.

5.2.4 Well Events after Placement

Anticipated well events after placement should be considered when selecting materials for barrier construction. The most common well events are positive and negative pressure testing of the plug.

5.3 Pumpable Sealants

The well abandonment sealant most commonly used is a blend of Portland cement and necessary additives for placement. The class or type of Portland cement varies with the choice being made by the end-user based on availability and functionality. However, other sealants have been successfully used, including but not limited to pozzolan blends, blast furnace slag blends, phosphate cement, hardening ceramics, resins, and geo-polymers. Several of these blends or sealant systems can also be combined to achieve specific purposes. Pumpable sealants can also contain special-purpose components (e.g., salts, lost circulation materials, expanding agents, etc.).

5.4 Natural

5.4.1 Collapsible Formations

In certain geologic settings, annular isolation may be established by post-drilling formation movement. Most typically, formations that may be capable of forming a natural annular barrier include salt (halite) and clay-containing formations, such as shale or mudstone. The mechanism by which a formation is displaced into an annulus is generally thought to be either by shear/tensile failure of the formation itself or by simple hydraulic movement (creep, swelling). To serve as a natural annular barrier, a formation shall have sufficient integrity to withstand the maximum anticipated pressure and possess a low permeability to prevent the transport of fluids through the displaced formation occupying the annulus.

NOTE Mudstone is a mixture of silts and clay-sized particles.

5.4.2 Qualification of Sealing Capability

The initial qualification of a natural annular barrier for a given field or basin is generally made using the results from a cement evaluation log followed by pressure testing of the barrier. Candidate natural annular barriers are identified stratigraphically by the gamma ray survey tools run in combination with the cement evaluation logging assemblies. Salt normally produces a low gamma ray count, while shale/mudstone typically produces a high gamma ray count, making either type of formation relatively easy to identify.

The cement evaluation log output parameters are then cataloged for the candidate natural annular barrier interval. If the initial log measurements indicate that a reasonably homogeneous solid occupies the annulus adjacent to the salt/shale/mudstone interval (as identified by the gamma ray survey), the casing is then perforated in the lower section of the candidate interval (or below the interval) and in the upper section of the candidate interval (or above the interval), then tested for pressure communication.

A cement retainer is then placed between the two sets of perforations. After stinging into the retainer with drill pipe or tubing, fluids are pumped through the lower set of perforations until a pre-determined pressure is obtained. The pressure in the annulus of the drill pipe/tubing and perforated casing above the retainer is monitored to ensure no pressure communication exists between the two sets of perforations. Alternatively, a retrievable packer can be used.

A single set of perforations may also be considered, provided surface monitoring of the annulus can verify any pressure communication.

Once confidence is established in the cement evaluation log acceptance criteria and pressure testing results on a few wells, the standalone logging results may be used to qualify the natural annular barrier for future well abandonments in offset wells.

5.4.3 Drilling Mud

Over time, a static mud may incur degradation or the natural separation of the weighing agents from the suspension fluid, creating a compressed bed layer. At the time of abandonment, the compressed bed layer may be suitable for barrier consideration. The integrity of the bed layer should be qualified for sealing capability as described in 5.4.2 and provide a sufficient height to meet the barrier requirements. Alternatively, a qualified bed layer may be used in combination or as part of a multi-component system to meet the barrier requirements.

5.5 Mechanical

Portland cement is considered the most accepted permanent abandonment material to form permanent well barriers. Cement typically provides permanent barrier characteristics for the planned service life and the anticipated well environment: low permeability, low porosity, interface seal, position, and durability.

Mechanical plugs are typically used as a reliable base for cement that is placed above the mechanical plug. They aid in the placement of cement, but are not typically considered a stand-alone permanent abandonment barrier.

Mechanical barriers typically contain metal or composite bodies with non-metal sealing elements (e.g., elastomer, thermoplastic elastomers). The durability of these elements is affected by the type of element used and well environment (temperature, pressure, fluid type). Degradation over the planned service life of a permanent abandonment may affect the ability of the element to maintain its barrier characteristics. The well environment may also raise corrosion concerns for the exposed metal components of the barrier.

See Figure 13 for an example of a barrier with a mechanical base.

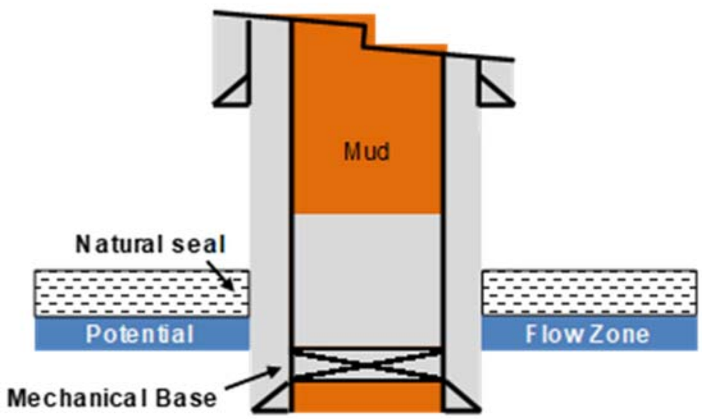


Figure 13—Example of a Barrier with a Mechanical Base

6 Installation

6.1 Placement Methodology

6.1.1 General

The wellbore should be static prior to cement plug placement. Fluid movement before, during, or after plug placement could affect the plug integrity. A static wellbore has no mud losses and no formation fluid influxes. The type and density of fluids left in the well between cement plugs may be stipulated by regulations.

Abnormally pressured or lost circulation zones can prevent fluid equilibrium in the wellbore. Mechanical devices, such as bridge plugs, inflatable packers, or cement retainers, may help to stabilize the well.

6.1.2 Volumes

The volume used for a particular plug should be determined from the planned length, hole diameter(s), placement method, and allowances for contamination. Some cement plug lengths may be specified by regulation.

6.1.3 Well Trajectory

Highly deviated or horizontal wellbores can affect the effectiveness of some plug placement techniques. This should be considered while planning the installation of the plug.

6.1.4 Displacement

6.1.4.1 General

Displacement methods include balanced plugs, pump and pull, perforation, wash and cement (PWC), inside blowout preventer (IBOP), and sacrificial workstring releasing tools.

6.1.4.2 Balanced Plug

The balanced plug method is commonly used. This method involves pumping the cement through a workstring until all fluids in the workstring and the annulus are placed such that fluid interfaces are stable. Fluid spacers are used ahead of and behind the cement to minimize contamination by the mud and improve bonding. After the plug has been placed with hydrostatically balanced fluid columns, the workstring is slowly pulled out of the plug to some distance above the top of the plug. Prior to cement plug placement, a homogeneous wellbore with the fluid density the same throughout improves the ability to effectively place a balanced cement plug.

6.1.4.3 Pump and Pull

This plug placement method pumps cement into the annulus (workstring by open hole or workstring by casing) at the same rate as pulling the workstring out of the hole. This method does not rely on hydrostatic forces to balance the cement plug.

This method of placement may have the following advantages:

— eliminates the problem of plug balancing in highly deviated wellbores where the cement plug does not create a hydrostatic differential;

— eliminates the problem of plug balancing when the cement and the drilling fluid are of similar density;

— reduces equivalent circulating densities (ECDs) during placement;

— allows for the placement of viscous or even slightly thixotropic cement with less risk of contamination.

This method of placement may have the following disadvantages:

— more involved calculations than for conventional balanced plugs in order to coordinate the pumping rate to the same rate as pulling the workstring out of the hole;

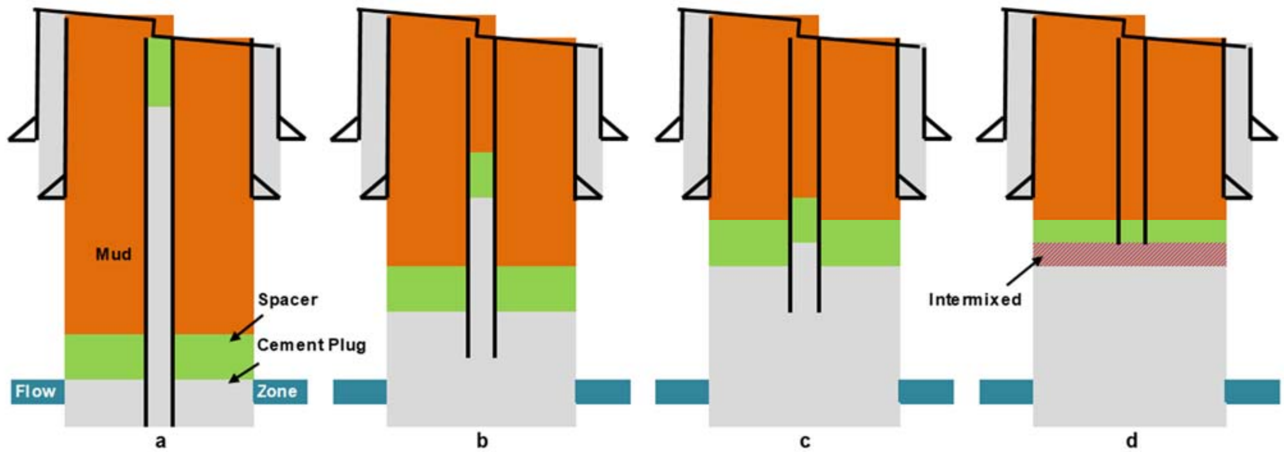
— cement plug may be compromised when the open hole diameter is not known, which makes the hole fill up prediction difficult;

— operational complexity;

— connections can be wet.

See Figure 14 for an example of the pump-and-pull method.

The pump-and-pull procedure is commonly used with coiled tubing. When used with pipe or tubing, to prevent u-tubing or free fall of fluids during connections of jointed pipe, the annular can be closed.



Key

a) workstring is located at the base of the cement plug, and a portion of cement is placed into the annulus; typical range can be 30 m (100 ft) to 90 m (300 ft) depending on hole size;

b) workstring is pulled out of the hole at the same rate of the surface pump rate (equivalent annular velocity) between the open hole and workstring; the cement in the annulus remains at the same height above the base of workstring;

c) displace until the cement is near the balance point of the plug if placed conventionally; the cement in the annulus remains at the same height above the base of workstring;

d) workstring is pulled out of hole and the cement at the top of the plug may become intermixed with the cement spacer or mud.

Figure 14—Example of a Pump and Pull Procedure

6.1.4.4 Perforation, Wash, and Cement (PWC)

PWC is a placement method to establish a continuous well barrier isolating the annulus and wellbore in a single operation. The method involves perforating the casing adjacent to the natural seal for the zone being isolated, washing the interval, then placing cement into the washed annulus and wellbore. There are typically two types of systems: the closed system (or “cup-type”) and the open system (or “jet-type”). For both systems, an important design parameter is the perforation size and density. Using the cup-type system, the perforations are generally smaller [e.g., < 19 mm ($^3/_4$ in.)] than those used for the jet-system, which are usually 25 mm (1 in.) or larger in diameter. The typical perforation density for the cup-type system is 39 shots/m (12 shots/ft), and for the jet-type system is 59 shots/m (18 shots/ft). The cup-type system is better suited for intervals where little or no cement exists in the annulus while the jet-type system can be used in fully cemented, partially cemented, or annuli void of cement.

The cup-type system consists of dual swab cups above and below nozzles. The washing fluid is forced out the nozzles between the swab cups and into the annulus through the perforations, i.e., “closed system.” The cement is then forced between the cups and into the annulus through the perforations while pulling the workstring. Once in the annulus, the fluid flows upward either in the annulus or in the casing by the drill pipe annulus. This depends on the tool position and presence of obstacles in the casing by the open hole annulus. Due to the closed system, the standpipe pressure can give continuous feedback of the cleaning and washing of the annulus.

The jet-type system relies on pressurized fluid flow through nozzles on a tool inside the casing that jets the fluid through the perforations into the annulus. The fluid can flow both through the perforations into the annulus behind and the casing by drill pipe annulus, i.e., “open system.” Typically, rotation of the workstring is 80 r/min to 120 r/min during the wash and cement placement phase. Consideration should be given to the casing size versus the jet-type tool size to ensure effective perforation washing and cement placement. Computational fluid dynamics modeling can be used to optimize the number, diameter, and orientation of the nozzles, as well as the differential pressure generated through the nozzles.

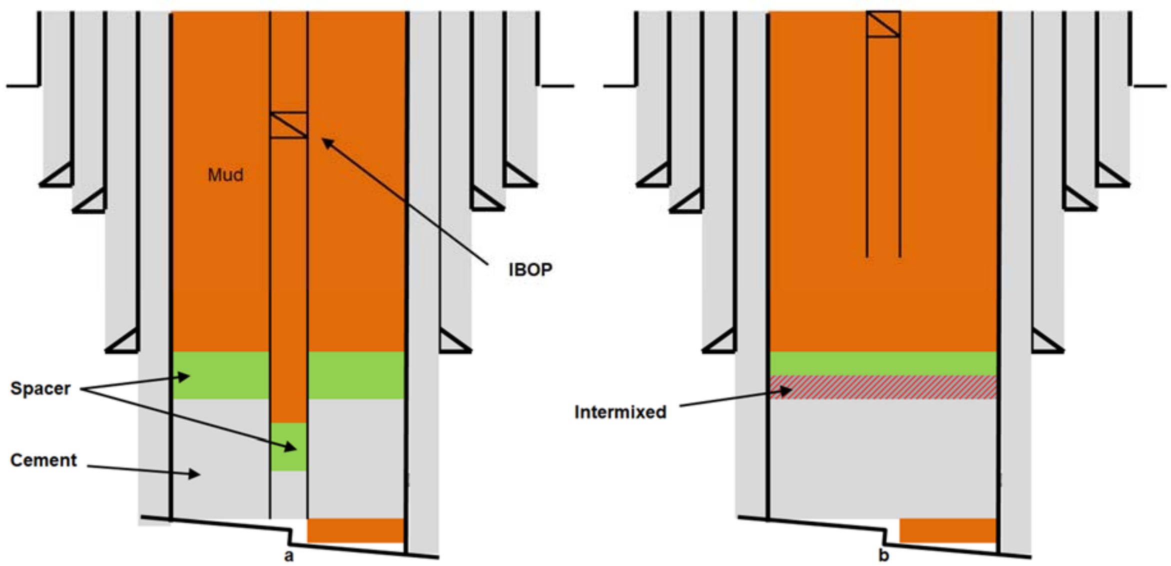
6.1.4.5 Inside Blowout Preventer (IBOP)

Using this method, an IBOP is placed in the workstring, preventing back-flow when pulling the workstring out of the hole. This method can provide an advantage when the hole size is not known accurately, or when it may be difficult to achieve balanced conditions.

The installation of the IBOP in the workstring is at a depth that it is close to surface when the workstring is pulled above the planned top of cement for the cement plug. This allows the cement to be displaced close to the end of the workstring before pulling slowly out of the hole. Once above the planned top of cement, circulation can be continued to clean up the excess mud, spacer, and cement from the wellbore. This method eliminates the need to perform balanced plug calculations, and may reduce the contamination risk in the body of the cement plug.

Due to the IBOP, the workstring is pulled wet until it is above the top of the cement plug. Additionally, the risk of swabbing the well requires mitigation by controlling the speed at which the workstring is pulled out of the hole through the cement plug.

See Figure 15 for an example of the IBOP method:



Key

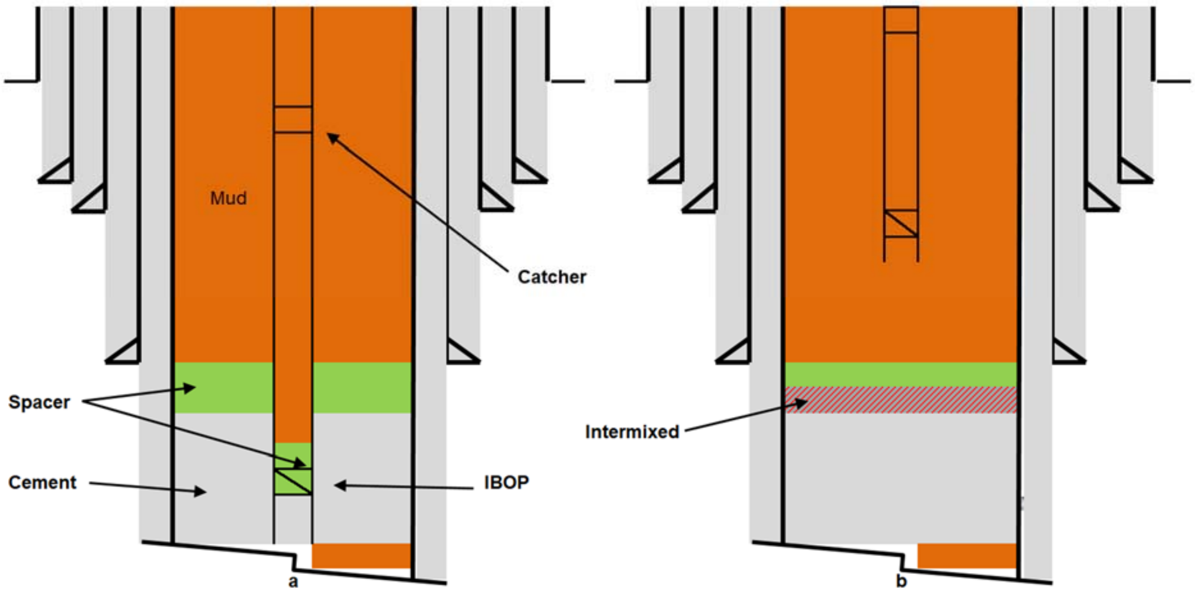
a) Displace cement to the end of the workstring and trap the volume in the string with the IBOP.
b) Pull the workstring out of the plug, wet, and allow the cement to slump into place.

Figure 15—Example of the IBOP Method to Set a Cement Plug

6.1.4.6 Modified IBOP

This method uses a non-ported deep-set workstring float (similar to a BHA float). A ball or dart catcher can be placed in the workstring to provide mechanical separation of fluids within the workstring that can improve displacement efficiency and the quality of the cement during placement (see 6.2.10). This method also carries the same advantages as the IBOP method. The use of a ball/dart catcher can provide a positive indication of the fluid positions and displacement volumes.

See Figure 16 for an example of the modified IBOP method used to set a cement plug.



Key

a) Displace cement to the end of the workstring, positive indication of displacement volume by dart/ball catcher, and trap the volume in the string with the IBOP.
b) Pull the workstring out of the plug, wet, and allow the cement to slump into place.

Figure 16—Example of the Modified IBOP Method to Set a Cement Plug

6.1.4.7 Sacrificial Workstring

A sacrificial workstring (tailpipe) should be considered when short thickening times (e.g., thixotropic designs) are required or when there are other circumstances that pose a high risk of compromising plug stability when the workstring is removed. This method may also be considered when long intervals are required to be plugged, as there is no additional time needed to pull out of the hole above the top of cement. Special tools are available that release the tailpipe using a ball drop mechanism. Other means of releasing the tailpipe are by shearing off at the end of the job or leaving the workstring in place until the cement has set, then cutting or backing off the pipe at the first free connection. Sacrificial workstring assemblies can be quickly fabricated out of locally available tubing and hardware. If necessary, such assemblies can be constructed out of any drillable material, such as aluminum, fiberglass, or composites. When using this method, effective placement around the workstring and the potential for fluid flow through the workstring should be considered.

NOTE Thixotropic designs exhibit rapid gel strength development when static, but when sheared, thin down and resume fluid mobility.

6.1.4.8 Squeezing

The cement squeeze method pumps cement to the desired interval to be isolated, usually through a workstring. Sufficient hydraulic pressure is applied to the cement, facilitating movement to the target area. The cement squeeze method is typically used for isolating completion intervals or open perforations inside cased hole. There are multiple squeeze placement methods used. Cement may be squeezed through a cement retainer or retrievable packer set in the casing to contain the squeeze pressure below the tool, or set as a balanced plug and then squeezed.

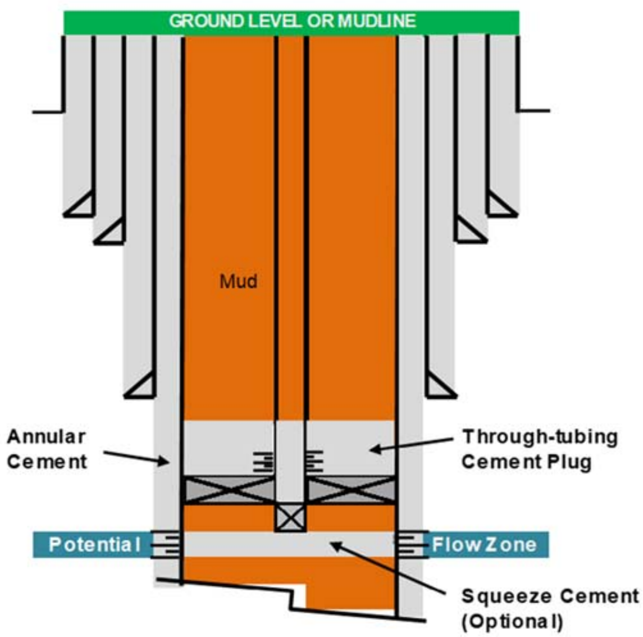
Alternatively, the bradenhead squeeze method is performed by circulating cement down to the squeeze interval. The backside of the wellbore is closed in, and pressure is applied from the surface to force cement into the target area. A hesitation squeeze is sometimes used to more effectively place the cement into all voids. Casing and wellhead seal assembly integrity should be considered before applying the bradenhead squeeze method.

6.1.4.9 Through-tubing

Where annular cement has been verified above a potential flow zone, it may be possible to place cement through the existing completion tubing to create a continuous permanent barrier. This is achieved by pumping cement down the existing completion tubing and into the tubing by casing annulus. The flow path is created by either placing holes or cutting the tubing above the existing production packer.

The isolation of the reservoir is typically done prior to the through-tubing placement of cement. This can be achieved by squeezing cement below the existing completion packer or by setting a mechanical plug inside the tubing.

See Figure 17 for an example of using the through-tubing method to isolate a potential flow zone.



NOTE Some abandonments may require the potential flow zone to be squeezed.

Figure 17—Through-tubing Method Isolating a Potential Flow Zone

Considerations for through-tubing placement include:

— mud should be solids-free and non-viscous to enable effective cement placement;

— condition of the existing annular cement;

— tubing and casing condition;

— evidence of sustained casing pressure (SCP);

— control lines and gauge cables.

6.1.4.10 Coiled Tubing

This method allows placement of cement plugs without rig intervention. The primary advantages include accurate control of volumes and depths. It is also effective in executing the pump-and-pull method for cement placement. Coiled tubing can be used for placing cement inside or through existing completion tubing.

6.1.4.11 Dump Bailer

The wireline or slickline conveyed dump bailer is typically used to deliver a small volume of cement to the desired location and is opened on impact or electronically triggered. The primary advantage is accurate control of the cement plug placement depth. The primary disadvantages are the limited cement volume that can be transported per run and contamination of the cement during placement. This method is typically used to place cement above a mechanical barrier, such as a bridge plug.

6.2 Balanced Plug Best Practices

6.2.1 Introduction

This section includes guidelines proven successful across the industry. Fundamental theory and principles are provided and emphasized, but allowances should be made for specific locations, wellbore conditions, and wellbore and workstring geometries that preclude the application for some of the preferred methodologies.

Planning a cement job requires understanding the existing well conditions and possible detrimental effects on the plug. Each plugging operation presents a common problem: a relatively small cement volume is placed in a large volume of mud. Muds can contaminate the cement, and after a waiting-on-cement (WOC) time, the result can be a weak, diluted, non-uniform, or unset plug. Sound engineering practices are important for effective plug placement of the cement.

NOTE The use of plug placement simulators can be considered.

6.2.2 Wellbore Preparation

Wellbore preparation plans shall be developed to maintain well control. The mud can have density and viscosity variations within the wellbore and active system. The hole should be conditioned to ensure the mud is homogeneous and all cuttings and gelled mud is removed, loosened, or minimized. If possible, a proper mud circulation plan should be used that results in stable circulating temperatures and uniform viscosity for plug placement. The pre-job circulation plan should be dictated by the required rate and volume for hole cleaning.

6.2.3 Plug Length

For abandonment plugs, the minimum plug length is typically dictated by regulatory requirements. Consideration should be given to the anticipated degree of contamination at the top and bottom of the plug to achieve the desired length of a competent plug. When planning cement plug length, consider rig capability and the time required to pull out of the plug. The pump-and-pull technique or a sacrificial string should be considered for placement of longer cement plugs when a single plug is required. Where a single long cement plug is not possible, several cement plugs may be set consecutively to achieve a desired cement length.

6.2.4 Cement Volume

The cement volume to achieve the desired plug length is dependent upon the hole and/or casing size. A caliper log is useful to improve determination of the hole size and the cement volume required for the desired plug length. When caliper log data are not available, local knowledge of lithology, drilling practices, mud type, and their effect on hole size should be relied upon to determine the cement volume required. Open hole excess should be considered with and without caliper data. Contamination of the top and bottom of the cement plug should be considered in the final plug volume.

6.2.5 Spacer Volume

The spacer volume ahead is typically sufficient to cover a minimum annular length of 150 m (500 ft). The spacer volume behind is calculated to balance the spacer volume ahead. The excess guidelines are the same as those used to determine the cement volume.

6.2.6 Spacer Design

Weighted viscous spacers should meet the following criteria.

- The friction pressure imparted by the spacer should be greater than the mud and less than the cement.
- The spacer density should be greater than the mud and less than the cement.
- Laboratory testing should verify the spacer is compatible with the mud and the cement.
- The spacer should be compatible with all formations it contacts.
- The spacer contains surfactants capable of providing preferential water wetting if a non-aqueous fluid (NAF) is in the well. Unless incorporated as part of a spacer train, NAFs should not be used as a spacer.

NOTE Water can be used in lieu of weighted viscous spacer when the mud in the well is a clear fluid.

6.2.7 Cement Design

6.2.7.1 Additives

In many cases, the only additives required are a retarder or an accelerator with an antifoam agent. A small concentration of dispersant may be required to improve mixability and pumpability. Fluid loss control is recommended for plugs set across long permeable intervals, and gas migration control additives may be required when setting plugs across gas zones with flow potential. Viscosifiers may be required for stability in high temperature or high pressure and both environments. An expanding agent can be added to impart bulk expansion to the set cement. Silica, typically 35 % by weight of cement (BWOC) or more, shall be used to stabilize the cement for strength retrogression at bottomhole static temperatures (BHST) greater than 110 °C (230 °F). The inclusion of salt in the cement may be warranted when cementing across salt formations. Shale inhibition can also be considered when appropriate.

6.2.7.2 Density

The cement slurry density should be higher than the mud density to achieve effective mud removal and maintain overbalance pressure. The density difference between the mud and the cement should be minimized to reduce the effect of fluid swapping below the plug due to buoyancy. In horizontal or near horizontal holes, the density difference between the mud and the cement should be minimized if feasible.

6.2.7.3 Strength

Cement strength and WOC time should be determined from ultrasonic cement analyzer laboratory data if possible. The cement strength should be tested at the top of the plug. Spacer and mud contamination can have an effect on strength development. Consideration should be given to testing the cement strength with spacer and/or mud contamination. Unless otherwise specified by regulations, a minimum strength of 3500 kPa (500 psi) is adequate.

6.2.7.4 Thickening Time

Cement slurry thickening time should account for the following when applicable:

- surface temperatures in mixing equipment;
- batch mix time;
- placement time;
- time to remove circulating equipment;

— time to pull the workstring a minimum of 150 m (500 ft) above the top of the plug;

— time to circulate the workstring clean; and

— a safety factor.

Excessive thickening times can increase the WOC time. A motor schedule in the consistometer, to simulate the cement remaining static while pulling out of the plug, is recommended. Accurate temperature data is important for designing the cement plug. The use of a numerical temperature simulator is recommended if available.

6.2.7.5 Free Fluid

Free fluid can result in a channel or a void in the cement into and through which formation fluid or gas can flow. It may also result in an underbalanced condition (through the water channel) initiating the flow. Control of free fluid is important for situations where there is the potential for flow. When plugs are set in deviated holes, the free fluid should be measured at a 45° angle with no evidence of settling, sedimentation, or channeling.

6.2.7.6 Fluid Loss

For plugs set in cased hole, cement slurry fluid loss control is typically not required. For plugs set in open hole or across perforations, the degree of fluid loss control should consider the formation permeability and the differential pressure (wellbore pressure minus pore pressure) encountered during plug placement. High fluid loss cement depositing a thick filter cake across a permeable zone could result in differential sticking the workstring.

6.2.8 Plug Base

6.2.8.1 General

When placing a cement plug on top of a lighter-density fluid, swapping due to buoyancy differences can occur. In cases where the plug is set off-bottom, a plug base shall be considered, especially when there is a large density differential between the mud and the cement or when the plug is set in a high-angle hole.

6.2.8.2 Mechanical Devices

Mechanical devices, such as umbrella-type tools, bridge plugs, retainers, or inflatable packers, are preferred for prevention of fluid swapping at the bottom of the plug.

6.2.8.3 Viscous Reactive Pills (VRP)

VRPs are effective in providing a base for cement plugs. These pills should be placed in the same method as the cement plug, with the top of the pill just below the planned depth for the bottom of the cement plug. VRPs should be designed so that when they come in contact with cement, they react to form an immobile mass. VRPs commonly use sodium silicate and bentonite as part of the formulation. The risk of sticking the workstring should be assessed, especially when using VRP in high-angle holes.

When setting plugs in bentonite water-based mud, a VRP may not be required as the cement can react with the bentonite in the mud. Compatibility testing should be used to identify the reactivity between the bentonite and the cement.

6.2.8.4 High-density Mud

High-density mud can be used as a base for a cement plug. When using this method, the hole below the plug should be filled with drilling fluid having a density greater than or equal to the cement density to prevent fluid swapping.

6.2.9 Pipe Movement

6.2.9.1 General

Pipe movement by rotation and/or reciprocation should be considered to aid in good mud displacement.

6.2.9.2 Rotation

Rotation has shown to be more effective for mud displacement than reciprocation when possible. Rotational speeds of 10 r/min to 20 r/min have shown to be effective. Rotational speeds shall not result with exceeding the maximum torque limits of connections, the top drive, and pipe bodies. Rotation should be applied only during cement placement (pumping) and should cease at the time the displacement is finalized.

6.2.9.3 Reciprocation

Reciprocation in conjunction with rotation is effective for conditioning the hole prior to setting the plug. Potential surge and swab effects should be considered. Once the spacer ahead is nearing the end of the workstring, stop reciprocating and place the workstring at the bottom plug depth. Reciprocating past this point can result in intermixing and contamination of the spacer with mud and the cement with spacer and mud.

6.2.10 Wiper Darts and Balls

The use of wiping devices reduces cement contamination inside of the workstring and prevents buildup of cement (scale) on the inner surface of the workstring.

When operationally feasible, one wiping device should be placed between the mud and the spacer ahead of the cement and another wiping device should be placed between the spacer and the cement. Placing wiping devices behind the cement could prevent the fluids from readily falling out of the workstring while pulling out of the plug, and can lead to cement being left inside the workstring. A wiping device should be pumped once the workstring is above the top of the plug to clean the inside of the workstring.

Wiper plugs and balls can be used with a plug catcher to indicate when the cement is in place and to prevent over-displacement. When using a plug catcher, it should be installed above the reduced diameter stinger with sufficient space to catch the dart or ball.

A wiping device should be appropriately sized for the workstring.

A launching device to prevent prolonged shutdowns while releasing balls or darts should be used.

6.2.11 Diverter Tool

A diverter tool aids in hole conditioning prior to plug-setting operations. Mud circulating through a diverter tool should aid in removing gelled and immobile mud from enlarged hole sections. An upward or sideways jetting diverter tool at the end of the workstring can improve plug placement operations. A diverter tool prevents the downward jetting action of the cement exiting the workstring from breaking any viscous pill placed as a plug base.

When using wiper darts, it is important to shear the dart after it lands so that there is not a positive shut-off in the string, but then immediately stop pumping to prevent over-displacement.

6.2.12 Reduced-diameter Stinger

Depending upon the size of the workstring and the casing or open hole, the use of a reduced-diameter stinger (tailpipe) at the bottom of the drill pipe or tubing may be required to improve plug placement by minimizing disturbance of the plug while pulling out of it. The stinger diameter should be large enough to provide acceptable annular velocity during placement while being small enough to minimize disturbance while pulling out of the plug.

See Table 1 for examples of selecting a reduced-diameter stinger for a given open hole or casing diameter.

Table 1—Reduced Diameter Stinger Selection

Open Hole/Casing Diameter		Stinger Diameter	
mm	in.	mm	in.
< 216	< 8.50	60 to 89	2.375 to 3.500
216 to 311	8.50 to 12.25	89 to 114	3.500 to 4.500
311 to 356	12.25 to 14.00	114 to 149	4.500 to 5.875
356 to 445	14.00 to 17.50	149 to 198	5.875 to 6.625
> 445	> 17.50	168	6.625

A stinger of uniform diameter should be longer than the combined length of the cement and spacer before removing from the plug. Setting a balanced plug across a mixed-diameter workstring can cause the initially balanced plug to unbalance as the workstring is removed, which can lead to cement contamination as well as pulling wet.

The workstring configuration should be considered when planning mechanical separation with balls and wiper darts.

6.2.13 Displacement

To ensure accurate control over displacement volume, the cement unit should be used for displacement. The pump rate should be slowed down in the range of 150 L/min to 350 L/min (1 bbl/min to 2 bbl/min) for the last 800 L to 1.5 m^3 (5 bbl to 10 bbl) of displacement. For large displacement volumes, displacing with the rig pumps may be considered. When using the rig pumps, ensure crosschecking is possible between the fluid pulled from the mud system and the physical measurement. The plug should be under-displaced to allow the cement to fall to the balance point and to pull the workstring dry.

Compressibility of the NAF should be accounted for in the displacement volume calculations. If this is not considered, there may unintended additional under-displacement volume. The displacement volume should consider the difference in capacity between the workstring and the stinger. This difference could result in plug contamination or pulling wet.

6.2.14 Pulling and Circulating Guidelines

Pull the workstring out of the plug slowly to minimize disturbance of the plug. Pull up at least 150 m (500 ft) above the top of the plug before circulating out any excess cement. If the ECD to reverse circulate exceeds fracture pressure, then circulate out the long way (conventionally). Monitor for losses while circulating above the plug. Loss circulation can lead to the plug disappearing or falling. When performing a squeeze after setting a balanced plug, it may be advantageous to pull a longer distance above the top of cement before holding squeeze pressure.

6.2.15 Setting Plugs in High-angle Wellbores

In horizontal or near horizontal wellbores, setting a balanced plug is challenging. When there are small differences in true vertical depth (TVD) between the top and bottom of the plug, there is a lack of differential pressure to cause the fluid interfaces inside and outside of the workstring to equalize. This places importance on displacement volume accuracy. There are tools such as ball catchers, plug catchers, and release tools available that aid in plug placement for high-angle wellbores. When these tools are not available, modification of the plug placement procedure should ensure the plug is sufficiently under-displaced, and pumping while pulling may be required.

7 Evaluation and Verification Criteria

7.1 General

Evaluation of barriers should verify the location and integrity when possible. Use well records to determine the location of existing well barriers and the method used for verification. Guidance provided in API 65-2 shall be used for barrier installation and potential flow zone isolation during well construction

7.2 Annulus

7.2.1 General

Annular barriers may include cement, packers, collapsible formations, degraded mud, or combinations thereof.

7.2.2 Evaluation of Surface Indicators

An annular barrier may be evaluated using surface indicators from the barrier installation. When cement is used as a barrier, post-cement job analysis, including material usage, cement job pumping data (such as pressure, fluid density, volumes, pump rates), and a pressure match, can provide indication of the cement position in the annulus.

If remedial cement treatments are performed, surface indicators of material usage, placement method, and job pumping data can give an initial indication of the barrier position.

In the case of an annular packer, the sequence of events, along with a weight recording and any pressures, may indicate a successful installation.

NOTE 1 A pressure match is a comparison of pressure data recorded during a cement job, also called a job signature, with pressure data obtained by a computer hydraulics simulation that includes wellbore geometry, fluids characteristics, volumes, and pump rates from the cement job.

NOTE 2 A pressure match can be one indicator of the top of cement location.

7.2.3 Cement Evaluation Tools

Annular barrier verification may be provided using cement evaluation tools. The cement evaluation tools include (but are not limited to) sonic and ultrasonic tools. These tools may be conveyed using a variety of methods (i.e., wireline, coiled tubing, drill pipe, etc.). The barrier installation, in addition to the barrier physical properties, which could help estimate the response of the cement evaluation tool, should be considered. See API 10TR1 for more details on cement evaluation using tools.

7.2.4 Communication Test

When a communication test is performed across an interval, a set of perforations should be shot at the bottom of the interval and a second set of perforations should be shot at the top. A packer should be set between the two sets of perforations, and pressure should be applied through the workstring into the lower perforations while the annulus is monitored for communication across the interval.

7.3 Inside Pipe (In-Pipe)

7.3.1 General

To evaluate and verify cement plugs inside pipe, the following methods may be used.

7.3.2 Physical or Mechanical Tests

7.3.2.1 General

Applying weight to a plug, also called tagging the plug, is a common method to verify the plug depth and confirm the plug withstands the applied force. However, the ability of the plug to provide a pressure seal is not confirmed using this method. A key advantage of this method is that it does not expose the wellbore to pressure. The plug can be weight tested with a workstring. Wireline tools and small workstrings can verify the depth of the plug top but not for weight testing.

For weight testing to be effective, the cement must have sufficient strength to support mechanical contact by the workstring or wireline tools. The wellbore and the mud must be in a condition such that the weight test is conducted safely.

7.3.2.2 Workstring

Weight testing may be accomplished by lowering the workstring until the plug is tagged and weight can be set down on the plug. The amount of weight set on the plug depends on the workstring and any regulatory requirements. A tally of the workstring in the hole when the plug is tagged can verify the plug depth. Washing down to remove a soft top is an important operational practice to avoid getting stuck.

If using a workstring to set a mechanical plug, the pipe tally can verify the plug setting depth. After setting and releasing the mechanical plug, it may be weight tested to verify it is properly set.

7.3.2.3 Wireline

Cement plug setting depths in open hole or cased hole may be wireline-verified by tagging the plug with a wireline assembly while noting the depth reading. This method does not allow additional weight to be set on the plug, but may offer operational advantages compared with using a workstring.

7.3.3 Hydraulic Tests

7.3.3.1 General

Pressure testing can establish the internal pressure integrity of the wellbore. Pressure testing is accomplished by applying a pressure differential across the plug through a negative pressure differential (inflow) or by applying a positive pressure differential (hydraulic pressure). Pressure testing is limited to cased holes where the wellbore can withstand the pressures applied.

Depending on the abandonment configuration, pressure testing may only be effective for the initial plug placed in the well. If pressure testing of the initial plug is successful, it may not be possible to verify the integrity of subsequent plugs with a pressure test.

7.3.3.2 Positive Test

If a positive test is performed, fluid should be pumped to pressure the wellbore to a set value based on the well abandonment configuration and/or any regulatory requirements. For example, a plug set to isolate a liner top may be tested to a pressure exceeding the test pressure of the casing shoe in which the liner was installed.

7.3.3.3 Inflow (Negative) Test

If an inflow test is performed, after isolating the plug (e.g., with a retrievable packer), the hydrostatic pressure in the well should be reduced until the pressure above the plug is less than the pore pressure of the zone(s) isolated by the plug. The well should be monitored to verify it is stable and there is no flow.

Annex A
(informative)

Balanced Plug Calculations

A.1 Multiple Workstrings and Annular Configurations

A.1.1 Introduction

This procedure is an example of one method used to calculate a balanced cement plug with multiple workstrings and annular configurations. For a balanced plug with a weighted spacer ahead placed in a wellbore using a multiple worksting, the following results should be given:

— total cement volume required;

— top of cement with the workstring in place;

— volume of spacer behind to balance the plug;

— top of the spacer with the workstring in place;

— top of the spacer with the workstring pulled out;

— displacement volume to balance the plug.

NOTE For field operations, the following calculations would round volumes to the nearest barrel and depths to the nearest foot.

A.1.2 Symbols

For the purpose of balanced plug calculations in USC units, the following symbols are used.

C_{i} is the capacity of the annular or workstring element "i" as given in Table A.1, expressed in barrels per foot;

$D_{\mathrm{c\text{-}wsi}}$ is the top depth of the balanced cement plug with the workstring in, expressed in feet;

$D_{\mathrm{c\text{-}wso}}$ is the top depth of the cement plug with the workstring out, expressed in feet;

$D_{\mathrm{sa\text{-}1}}$ is the calculated top depth of the spacer ahead in the annulus of the 5 $^{7}/_{8}$ workstring across 16-in. casing, expressed in feet;

$D_{\mathrm{s\text{-}wsi}}$ is the top depth of the spacer ahead and behind with the workstring in, expressed in feet;

$D_{\mathrm{s\text{-}wso}}$ is the top depth of the spacer with the workstring out, expressed in feet;

$D_{\mathrm{ws\text{-}DP}}$ is the ending depth of the 6 $^{5}/_{8}$ in. 34 lb/ft drill pipe, expressed in feet;

$D_{\mathrm{ws\text{-}DP1}}$ is the ending depth of the 6 $^{5}/_{8}$ in. 27 lb/ft drill pipe 1, expressed in feet;

$D_{\mathrm{ws\text{-}DP2}}$ is the ending depth of the 6 $^{5}/_{8}$ in. 27 lb/ft drill pipe 2, expressed in feet

D_0 is the bottom depth of the calculation volume, expressed in feet;

D_1 is the top depth of the calculation volume, expressed in feet;

H_i is the calculated height of element "i" (volume V_{iC}), expressed in feet;

H_{10} is the height of spacer ahead across element 10 (annulus 6 $^5/_8$ in. DP2 workstring, casing 16 in.), expressed in feet;

H_{11} is the height of spacer behind inside element 11 (6 $^5/_8$ in. DP2 workstring), expressed in feet;

PV_i is the pairing volume of the section "i", expressed in barrels;

PV_{iC} is the corrected pairing volume of the section "i", expressed in barrels;

PV_{iR} is the remaining pairing volume of the section "i", expressed in barrels;

V_{TP} is total cement plug volume, expressed in barrels;

V_{TS} is total spacer volume (spacer ahead and spacer behind), expressed in barrels;

V_{dt} is the displacement volume to balance plug, expressed in barrels;

V_i is the calculated volume of the element "i", expressed in barrels;

V_{iC} is the corrected cement volume for the element "i" (i = 8 or 9), expressed in barrels;

V_{iR} is the remaining volume for spacer in the element "i" (i = 8 or 9), expressed in barrels;

V_{sa} is the volume of spacer ahead, expressed in barrels;

V_{sb} is the volume of spacer behind, expressed in barrels;

V_{11R} is the remaining volume element 11, inside the 6 $^5/_8$ in. DP2 workstring and above the spacer behind, expressed in barrels;

V_{10S} is the remaining spacer ahead volume in element 10 (6 $^5/_8$ in. DP2, casing 16 in.), expressed in barrels;

V_{11S} is the balanced spacer volume behind in element 11 (6 $^5/_8$ in. DP2 workstring), expressed in barrels.

A.2 Balanced Plug Calculations Example

A.2.1 Wellbore and Workstring

The following example shows how to calculate a 1000 ft balanced cement plug with 160 bbl of weighted spacer ahead for the given wellbore and multiple workstring shown in Figure A.1:

Please note Figure A.1 is not to scale.

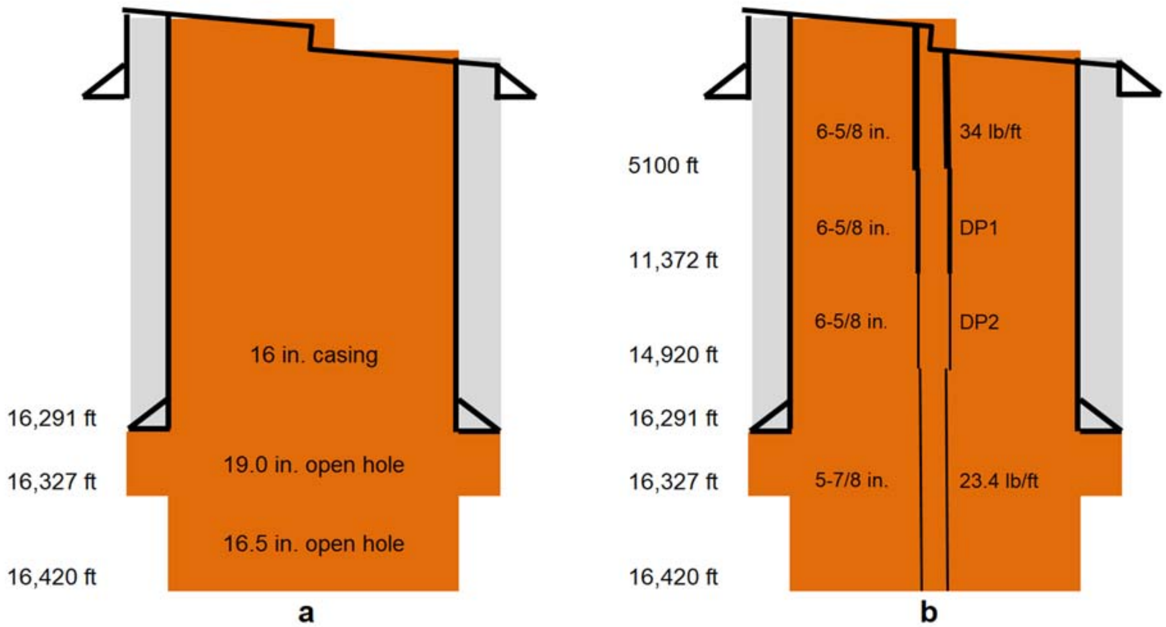


Figure A.1—Example Wellbore with a) Workstring Out and b) Workstring In

See Table A.1 for the workstring, casing, and open hole capacities.

Table A.1—Wellbore Capacities for Calculations: Example

Configuration	Depth ft	Length ft	Capacity bbl/ft	Capacity Symbol
6 5/8 in. 34 lb/ft drill pipe (DP)	5100	5100	0.02905	C_{11}
6 5/8 in. 27 lb/ft drill pipe 1 (DP1)	11,372	6272	0.03180	C_{10}
6 5/8 in. 27 lb/ft drill pipe 2 (DP2)	14,920	3548	0.03238	C_9
5 7/8 in. 23.4 lb/ft drill pipe	16,420	1500	0.02510	C_4
16 in. 109.6 lb/ft casing	16,291	—	0.21281	C_3
19.0 in. open hole (OH)	16,327	36	0.35069	C_2
16.5 in. open hole (OH)	16,420	93	0.26447	C_1
5 7/8 in. drill pipe x 16.5 in. open hole	—	93	0.23094	C_5
5 7/8 in. drill pipe x 19.0 in. open hole	—	36	0.31716	C_6
5 7/8 in. drill pipe x 16 in. casing	—	1371	0.17928	C_7
6 5/8 in. DP2 × 16 in. casing	—	3548	0.17018	C_8

NOTE DP1 and DP2, though similar, have connection differences that result in different capacities.

A.2.2 Total Cement Volume Required

Find the volume of cement required to set a 1000 ft balanced plug on bottom, with no workstring in place. Figure A.2 demonstrates the individual calculation volumes to determine the total volume (V_{TP}).

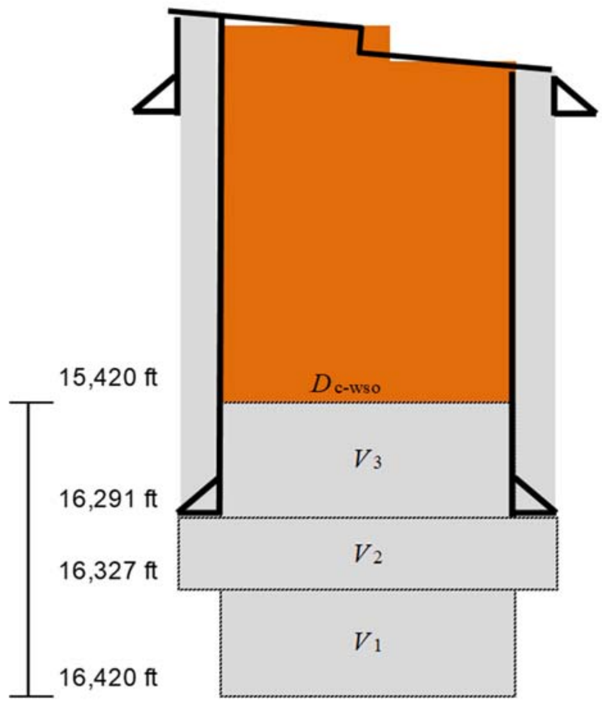


Figure A.2—Calculation Volumes for the Total Cement Volume

The total cement volume is the summation of the individual calculation volumes. See Equations (A.1) to (A.4).

$$V_{TP} = V_1 + V_2 + V_3 \tag{A.1}$$

where:

V_{TP} is total plug volume, expressed in bbl;

V_1 is the volume of the 16.5 in. open hole, expressed in bbl;

V_2 is the volume of the 19.0 in. open hole, expressed in bbl;

V_3 is the volume of the 16 in. casing to the top of cement, expressed in bbl;

and:

$$V_1 = (D_0 - D_1) \times C_1 \tag{A.2}$$

$$V_2 = (D_0 - D_1) \times C_2 \tag{A.3}$$

$$V_3 = (D_0 - D_1) \times C_3 \tag{A.4}$$

where:

D_0 is the bottom depth of the calculation volume, expressed in ft;

D_1 is the top depth of the calculation volume, expressed in ft;

C_1 is the capacity of the 16.5 in. open hole, expressed in bbl/ft;

C_2 is the capacity of the 19.0 in. open hole, expressed in bbl/ft;

C_3 is the capacity of the 16 in. casing, expressed in bbl/ft;

thus:

$$V_1 = (16,420 - 16,327) \times 0.26447 = 24.59 \text{ bbl}$$

$$V_2 = (16,327 - 16,291) \times 0.35069 = 12.62 \text{ bbl}$$

$$V_3 = (16,291 - 15,420) \times 0.21281 = 185.36 \text{ bbl}$$

and for the cement total volume:

$$V_{TP} = 24.59 + 12.62 + 185.36 = 222.58 \text{ bbl}$$

A.2.3 Top of Balanced Cement with the Workstring In

Find the top of cement for the 1000 ft balanced cement plug, with the workstring in, calculated according to the workstring (see A.2.1). Figure A.3 demonstrates the individual calculation volumes to determine the top of cement volume ($D_{c\text{-wsi}}$).

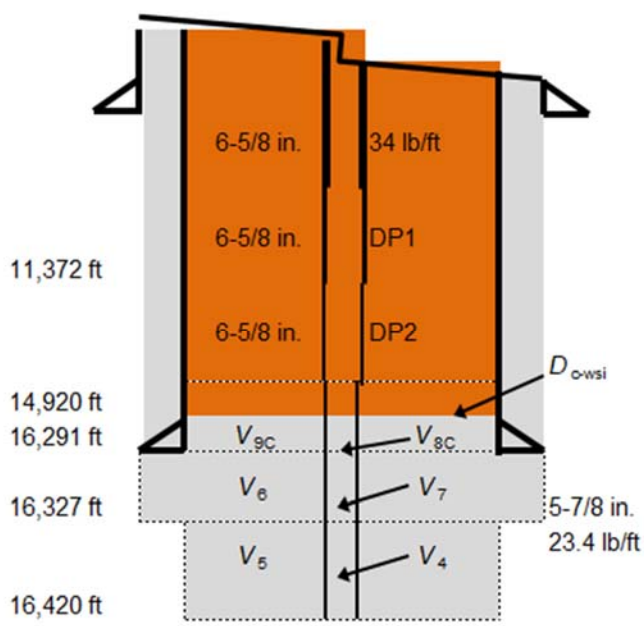


Figure A.3—Calculation Volumes for Top of Cement with Workstring In

Using the total cement volume required for the plug with the workstring out (V_{TP}), fill up the pairing calculation volumes (V_4 to V_5, V_6 to V_7, V_8 to V_9) to identify where one of the pairing calculation volumes are only partially filled, starting from the bottom and moving up using Equations (A.5) to (A.13).

$$V_4 = (D_0 - D_1) \times C_4 \tag{A.5}$$

$$V_5 = (D_0 - D_1) \times C_5 \tag{A.6}$$

$$V_6 = (D_0 - D_1) \times C_6 \tag{A.7}$$

$$V_7 = (D_0 - D_1) \times C_4 \tag{A.8}$$

$$V_8 = (D_0 - D_1) \times C_4 \tag{A.9}$$

$$V_9 = (D_0 - D_1) \times C_7 \tag{A.10}$$

where:

V_4 is the inside volume of the 5 7/8 in. workstring across 16.5 in. open hole, expressed in bbl;

V_5 is the annular volume of the 5 7/8 in. by 16.5 in. open hole configuration, expressed in bbl;

V_6 is the annular volume of the 5 7/8 in. by 19.0 in. open hole configuration, expressed in bbl;

V_7 is the inside volume of the 5 7/8 in. workstring across 19.0 in. open hole, expressed in bbl;

V_8 is the inside volume of the 5 7/8 in. workstring across 16 in. casing, expressed in bbl;

V_9 is the annular volume of the 5 7/8 in. by 16 in. casing configuration, expressed in bbl;

and:

C_4 is the capacity of the 5 7/8 in. workstring, expressed in bbl/ft;

C_5 is the annular capacity of the 5 7/8 in. workstring by 16.5 in. configuration, expressed in bbl/ft;

C_6 is the annular capacity of the 5 7/8 in. workstring across 19.0 in. open hole, expressed in bbl/ft;

C_7 is the annular capacity of the 5 7/8 in. workstring by 16 in. casing configuration, expressed in bbl/ft.

Therefore, calculate the first pairing volume across the 16.5 in. open hole:

$$PV_1 = V_4 + V_5 \tag{A.11}$$

where:

PV_1 is the pairing volume for the 16.5 in. open hole, expressed in bbl;

thus:

$$V_4 = (16{,}420 - 16{,}327) \times 0.02510 = 2.33 \text{ bbl}$$

$$V_5 = (16{,}420 - 16{,}327) \times 0.23094 = 21.47 \text{ bbl}$$

$$PV_1 = 2.33 + 21.47 = 23.80 \text{ bbl}$$

As 23.8 bbl is less than V_{TP} continue to the next pairing volume across 19.0 in. open hole:

$$PV_2 = V_6 + V_7 \tag{A.12}$$

where:

PV_2 is the pairing volume for the 19 in. open hole, expressed in bbl;

thus:

$$V_6 = (16{,}327 - 16{,}291) \times 0.31716 = 11.42 \text{ bbl}$$

$$V_7 = (16{,}327 - 16{,}291) \times 0.02510 = 0.90 \text{ bbl}$$

$$PV_2 = 11.42 + 0.90 = 12.32 \text{ bbl}$$

As 36.12 bbl (PV_1 + PV_2) is less than V_{TP}, continue to the next pairing volume across the 16 in. casing:

$$PV_3 = V_8 + V_9 \tag{A.13}$$

where:

PV_3 is the pairing volume for the 16 in. casing, expressed in bbl;

thus:

$$V_8 = (16{,}291 - 14{,}290) \times 0.02510 = 50.23 \text{ bbl}$$

$$V_9 = (16{,}291 - 14{,}290) \times 0.17928 = 358.74 \text{ bbl}$$

$$PV_3 = 50.23 + 358.74 = 408.97 \text{ bbl}$$

As 445.09 bbl (PV_1 + PV_2 + PV_3) is greater than V_{TP}, determine the height of cement across the 16 in. casing. The total plug volume remaining has to be balanced across the 16 in. casing and the corrected PV_{3C} should be:

$$PV_{3C} = V_{TP} - (PV_1 + PV_2) \tag{A.14}$$

thus:

$PV_{3C} = 222.58 - (23.80 + 12.32) = 186.46$ bbl

Therefore, Equation (A.13) becomes Equation (A.15):

$$PV_{3C} = V_{8C} + V_{9C} = 186.46 \text{ bbl} \tag{A.15}$$

where:

V_{8C} is the cement volume inside of the 5 7/8 in. workstring across 16 in. casing, expressed in bbl;

V_{9C} is the annular cement volume of the 5 7/8 in. by 16 in. casing configuration, expressed in bbl;

Equation (A.16) (same cement heights in V_8 and V_9) can be rearranged into Equation (A.17)

$$\frac{V_{8C}}{C_4} = \frac{V_{9C}}{C_7} \tag{A.16}$$

or

$$V_{8C} \times C_7 = V_{9C} \times C_4 \tag{A.17}$$

Substituting Equation (A.15) into Equation (A.17) gives Equation (A.18):

$$V_{8C} \times C_7 = (186.46 - V_{8C}) \times C_4 \tag{A.18}$$

so solving for V_{8C} (cement volume inside of the 5 7/8 in. workstring across 16 in. casing):

$$V_{8C} \times C_7 = (186.46 \times C_4) - V_{8C} C_4$$

$$V_{8C} C_7 + V_{8C} C_4 = 186.46 \times C_7$$

$$V_{8C} (C_7 + C_4) = 186.46 \times C_4$$

$$V_{8C} (0.17928 + 0.02510) = 186.46 \times 0.02510$$

$$V_{8C} (0.20438) = 4.6801$$

$$V_{8C} = 4.6801 / 0.20438 = 22.90 \text{ bbl}$$

and for V_{9C} (annular cement volume of the 5 7/8 in. by 16 in. casing):

$$186.46 = 22.90 + V_{9C}$$

$$V_{9C} = 163.56 \text{ bbl}$$

For the pairing volume PV_{3C}, the heights of V_{8C} and V_{9C} are equal, and are determined according to Equation (A.16),and using Equation (A.19) and Equation (A.20):

$$H_8 = \frac{V_{8C}}{C_4} \tag{A.19}$$

$$H_9 = \frac{V_{9C}}{C_7} \tag{A.20}$$

where:

H_8 is the cement height inside the 5 7/8 in. workstring across 16 in. casing, expressed in ft;

H_9 is the cement height inside the 5 7/8 in. by 16 in. configuration, expressed in ft;

so:

$$H_8 = 22.90 / 0.02510 = 912.35 \text{ ft}$$

$$H_9 = 163.56 / 0.17928 = 912.32 \text{ ft}$$

The top, either inside the workstring or in the annulus, of the cement with the workstring in is the difference between the top of the previous pairing volumes—for this case PV_2—and the height of the remaining cement volume in PV_3, either H_8 or H_9.

$$D_{\text{c-wsi}} = 16{,}291 - 912.3 = 15{,}378.7 \text{ ft}$$

where:

$D_{\text{c-wsi}}$ is the top depth of the balanced cement plug in either volume segment, expressed in ft.

A.2.4 Volume of Spacer Behind to Balance the Plug

Find the volume of spacer behind (V_{sb}) to balance the 1000 ft cement plug, with the workstring in, calculated according to A.2.1 using a spacer volume ahead (V_{sa}) of 160 bbl. The same approach as the requirements given in A.2.3 is followed to determine which pairing volumes remain partially filled with the 160 bbl of spacer volume ahead (V_{sa}).

Using the top of cement with the workstring in ($D_{\text{c-wsi}}$), determined as specified in A.2.3, calculate the potential top (depth, $D_{\text{sa-1}}$) of the spacer ahead in the annulus of the 5 7/8 in. workstring across 16 in. casing and compare this against the ending depth of 6 5/8 in. DP2 workstring ($D_{\text{ws-DP2}}$) to check if the top of the spacer ahead is in the pairing volume (V_9 to V_8).

From Equation (A.10):

$$D_{\text{sa}-1} = D_{\text{c-wsi}} - \frac{V_{\text{sa}}}{C_7} \tag{A.21}$$

$$D_{\text{sa-1}} = 15{,}378.7 - \left(160 / 0.17928\right) = 14{,}486.2 \text{ ft}$$

where:

C_7 is the annular capacity of the 5 7/8 in. by 16 in. casing configuration, expressed in bbl/ft.

The ending depth of 14,920 ft of the 6 5/8 in. DP2 compared to the depth $D_{\text{sa-1}}$ of 14,486.2 ft, indicates the top of the spacer ahead is in the next pairing volume (V_{10} to V_{11}) across the 6 5/8 in. DP2 workstring. Figure A.4 demonstrates the individual calculation volumes to determine the volume of spacer behind to balance (V_{sb}).

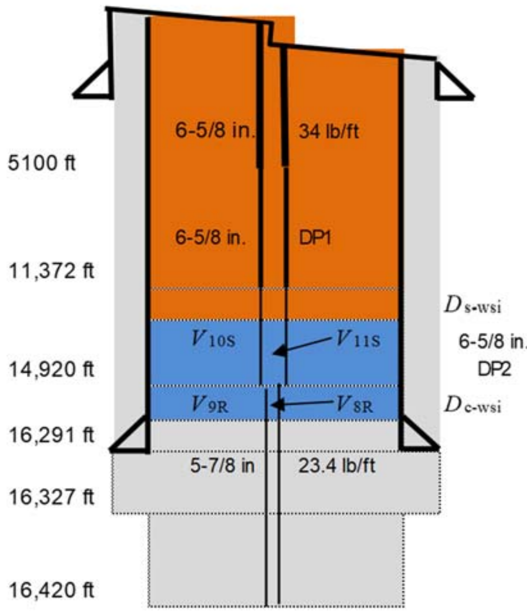


Figure A.4—Calculation Volumes for Spacer Behind with Workstring In

PV_3 was partially filled with cement according to A.2.3. Part of the 160 bbl spacer volume would fill the remaining annular volume (V_{9R}). The difference between the 160 bbl of spacer volume ahead and V_{9R} constitutes the calculations for V_{10S}.

The volume of the spacer ahead constituted in V_{9R} is the difference from $D_{\text{c-wsi}}$ and $D_{\text{ws-DP2}}$ (top of 5 7/8 in. workstring) for PV_3. Using Equation (A.10) for Equation (A.22):

$$V_{9R} = \left(D_{\text{c-wsi}} - D_{\text{ws-DP2}}\right) \times C_7 \tag{A.22}$$

where:

V_{9R} is the volume remaining in V_{9R}, expressed in bbl;

$D_{\text{c-wsi}}$ is the top depth of the cement in volume segment V_9, expressed in ft;

$D_{\text{ws-DP2}}$ is the top depth of volume segment V_9, i.e., ending depth of 6 5/8 in. DP2 workstring, expressed in ft;

C_7 is the capacity of the 5 7/8 in. workstring by 16 in. casing configuration, expressed in bbl/ft;

thus:

$$V_{9R} = \left(15{,}378.7 - 14{,}920\right) \times 0.17928 = 82.24 \text{ bbl}$$

As the total volume of spacer ahead (V_{sa}) is 160 bbl, the annular volume remaining (V_{10S}) in the next pairing volume (PV_4) is 77.76 bbl (V_{sa} - V_{9R}). From V_{10S}, the balanced volume of spacer behind is determined in PV_4. Determine the annular height of V_{10S} using Equation (A.23), which is similar to Equation (A.19):

$$H_{10} = \frac{V_{10S}}{C_8} \tag{A.23}$$

where:

H_{10} is the height inside the 6 5/8 in. DP2 by 16 in. casing configuration, expressed in ft;

V_{10S} is the remaining spacer ahead volume across the 6 5/8 in. DP2 by 16 in. casing configuration, expressed in bbl;

C_8 is the annular capacity of the 6 5/8 in. DP2 by 16 in. casing, expressed in bbl/ft.

thus:

$$H_{10} = (160 - 82.24) / 0.17018 = 77.76 / 0.17018$$

$$H_{10} = 456.9 \text{ ft}$$

To balance the spacer behind in PV_4, the height in the annulus (H_{10}) equals the height inside the 6 5/8 in. DP2 workstring (H_{11}). Applying this to Equation (A.23), Equation (A.24) is:

$$H_{11} \times C_9 = H_{10} \times C_9 = V_{11S} \tag{A.24}$$

where:

H_{11} is the height inside the 6 5/8 in. DP2 workstring, expressed in ft;

C_9 is the capacity of the 6 5/8 in. DP2 workstring, expressed in bbl/ft;

V_{11S} is the balanced spacer volume behind in 6 5/8 in. DP2 workstring, expressed in bbl.

thus:

$$V_{11S} = 456.9 \times 0.03238 = 14.79 \text{ bbl}$$

Since it was established PV_3 is filled due to V_{sa}, the corresponding volume remaining inside the 5 7/8 in. workstring to be consumed needs to be determined (V_{8R}).

Using the top of cement with the workstring in ($D_{c\text{-}wsi}$), determined according to A.2.3 and using Equation (A.22), Equation (A.25) is:

$$V_{8R} = \left(D_{c\text{-}wsi} - D_{ws\text{-}DP2}\right) \times C_8 \tag{A.25}$$

where:

V_{8R} is the volume remaining in V_8 (spacer behind), expressed in bbl;

$D_{ws\text{-}DP2}$ is the top depth of volume segment V_{8R}, i.e., ending depth of 6 5/8 in. DP2 workstring, expressed in ft;

C_8 is the capacity of the 5 7/8 in. workstring, expressed in bbl/ft.

thus:

$$V_{8R} = (15,378.7 - 14,920) \times 0.02510 = 11.51 \text{ bbl}$$

Therefore, the total volume of spacer behind is seen in Equation (A.26):

$$V_{sb} = V_{8R} + V_{11S} \quad \text{(A.26)}$$

where:

V_{sb} is the total volume of spacer behind to balance, expressed in bbl;

V_{8R} is the balanced spacer volume behind in 5 7/8 in. workstring, expressed in bbl;

V_{11S} is the balanced spacer volume behind in 6 5/8 in. DP2 workstring, expressed in bbl;

thus:

$$V_{sb} = 11.51 + 14.79 = 26.30 \text{ bbl}$$

A.2.5 Top of Spacer with the Workstring In

To determine the top of the spacer with the workstring in ($D_{s\text{-}wsi}$), since the height of the spacer consumed inside V_{11} is known from H_{11} as specified in Equation (A.24), the difference is taken between the bottom depth of the pairing volumes (PV_4) and H_{11}. This results in Equation (A.27):

$$H_{11} = D_{ws\text{-}DP2} - D_{s\text{-}wsi} \quad \text{(A.27)}$$

where:

H_{11} is the height of spacer inside the 6 5/8 in. DP2 workstring, expressed in ft;

$D_{s\text{-}wsi}$ is the top depth of the spacer in either volume segment (V_{10R} or V_{11}), i.e., with the workstring in, expressed in ft;

$D_{ws\text{-}DP2}$ is the top depth of volume segment V_{8R}, i.e., ending depth of 6 5/8 in. DP2 workstring, expressed in ft;

thus:

$$456.9 = 14,920 - D_{s\text{-}wsi}$$

$$D_{\text{s-wsi}} = 14{,}920 - 456.9$$

$$D_{\text{s-wsi}} = 14{,}463.1 \text{ ft}$$

A.2.6 Top of Spacer with the Workstring Out

The total volume of spacer (V_{TS}) used to balance the plug is the summation of the V_{sa} and V_{sb}, which is 186.3 bbl. As the balanced plug is 1000 ft with the workstring out, the height of the total spacer volume can be determined. Figure A.5 demonstrates the calculation volumes to determine the top of the spacer with the workstring out.

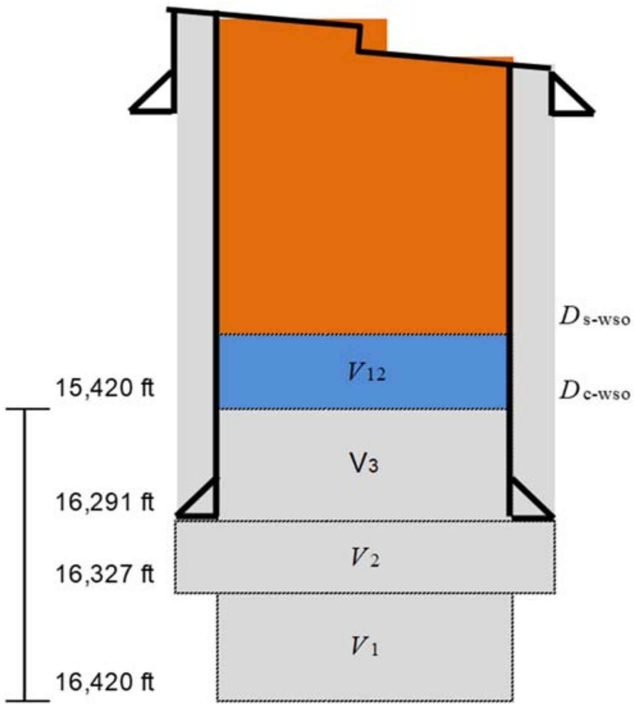


Figure A.5—Calculation Volumes for Spacer Behind with Workstring Out

Using Equation (A.4), V_{12} (i.e., V_{TS}) becomes Equation (A.28):

$$V_{TS} = V_{12} = \left(D_{\text{c-wso}} - D_{\text{s-wso}}\right) \times C_3 \tag{A.28}$$

where:

- V_{TS} is the spacer volume inside the 16 in. casing, expressed in bbl;
- $D_{\text{c-wso}}$ is the top depth of the cement volume inside the 16 in. casing, expressed in ft;
- $D_{\text{s-wso}}$ is the top depth of the spacer volume inside the 16 in. casing, expressed in ft;
- C_3 is the capacity of the 16 in. casing, expressed in bbl/ft;

thus:

$$D_{\text{s-wso}} = D_{\text{c-wso}} - \left(\frac{V_{12}}{C_3}\right)$$

$$D_{\text{s-wso}} = 15,420 - \left(186.30 / 0.21281\right) = 15,420 - 875.4$$

$$D_{\text{s-wso}} = 14,544.6 \text{ ft}$$

A.2.7 Displacement Volume to Balance the Plug

The displacement volume (V_{dt}) to balance the plug would be the inside volume of the workstring to the top depth of the spacer determined according to A.2.5. To determine this volume, the remaining capacities in the workstring are calculated together from bottom to top. Figure A.6 illustrates the individual volume calculations.

The displacement volume in 6 5/8 in. DP2 workstring would be the remaining capacity ($V_{11\text{R}}$) since part is consumed with $V_{11\text{S}}$ (part of spacer behind). Therefore, applying Equation (A.25), Equation (A.29) is:

$$V_{11\text{R}} = \left(D_{\text{s-wsi}} - D_{\text{ws-DP1}}\right) \times C_9 \qquad \text{(A.29)}$$

where:

$V_{11\text{R}}$	is the remaining volume element 11, above spacer behind, inside the 6 5/8 in. DP2 workstring, expressed in bbl;
$D_{\text{s-wsi}}$	is the top depth of the spacer in either volume segment with the workstring in, expressed in ft;
$D_{\text{ws-DP1}}$	is the top depth of volume segment $V_{11\text{R}}$, i.e., ending depth of 6 5/8 in. DP1 workstring, expressed in ft;
C_9	is the capacity of the 6 5/8 in. DP2 workstring, expressed in bbl/ft.

thus:

$$V_{11\text{R}} = \left(14,463.1 - 11,372\right) \times 0.03238 = 100.09 \text{ bbl}$$

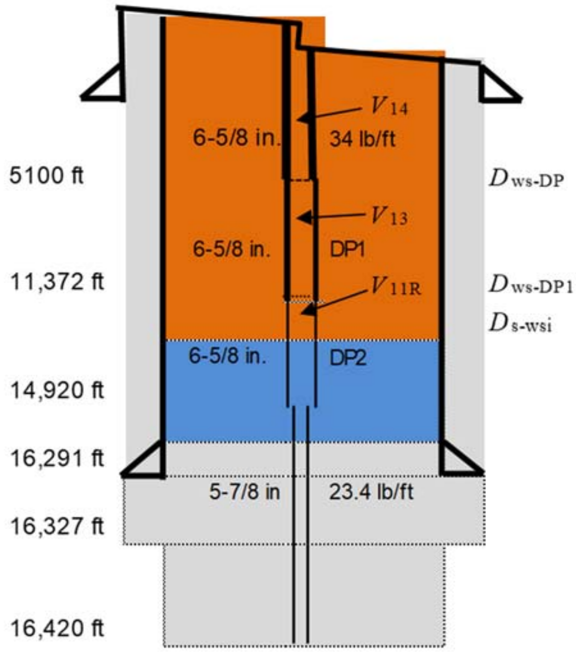


Figure A.6—Calculation Volumes for Displacement

The next volume calculation is V_{13} as seen in Equation (A.30): the capacity of the 6 5/8 in. DP1 workstring.

$$V_{13} = \left(D_{\text{ws-DP1}} - D_{\text{ws-DP}}\right) \times C_{10} \tag{A.30}$$

where:

V_{13}	is the volume inside the 6 5/8 in. DP1 workstring, expressed in bbl;
$D_{\text{ws-DP1}}$	is the top depth of volume segment V_{13}, i.e., top depth of 6 5/8 in. DP1 workstring, expressed in ft;
$D_{\text{ws-DP}}$	is the ending depth of volume segment V_{13}, i.e., ending depth of 6 5/8 in. DP workstring, expressed in ft;
C_{10}	is the capacity of the 6 5/8 in. DP1 workstring, expressed in bbl/ft;

thus:

$$V_{13} = (11{,}372 - 5100) \times 0.03180 = 6272 \times 0.03180$$

$$V_{13} = 199.45 \text{ bbl}$$

The next volume calculation is V_{14} as seen in Equation (A.31): the capacity of the 6 5/8 in. 34 lb/ft workstring to surface.

$$V_{14} = D_{\text{ws-DP}} \times C_{11} \tag{A.31}$$

where:

V_{14} is the volume inside the 6 5/8 in. 34 lb/ft workstring, expressed in bbl;

$D_{\text{ws-DP}}$ is the ending depth of volume segment V_{14}, i.e., length of 6 5/8 in. 34 lb/ft workstring to surface, expressed in ft;

C_{11} is the capacity of the 6 5/8 in. 34 lb/ft workstring, expressed in bbl/ft;

thus:

$$V_{14} = 5100 \times 0.02905$$

$$V_{14} = 148.16 \text{ bbl}$$

Therefore, the total displacement volume would be seen in Equation (A.32):

$$V_{\text{dt}} = V_{14} + V_{13} + V_{11\text{R}} \tag{A.32}$$

where:

V_{dt} is the total displacement volume to balance the plug, expressed in bbl;

thus:

$$V_{\text{dt}} = 148.16 + 199.45 + 100.09$$

$$V_{\text{dt}} = 447.70 \text{ bbl}$$

A.2.8 Balanced Cement Plug Calculation Summary

For the 1000 ft balanced plug example above, at 16,420 ft,, in a 16.5-in. open hole, below a 16-in. 109.6 lb/ft casing, with 160 bbl of weighted spacer volume ahead, placed in a wellbore using a multiple workstring configuration of 6 5/8 in., with a stinger 5 7/8 in. (see A.2.1), the calculated volumes are (volumes rounded for a field application):

— total cement volume: 223 bbl;

— volume of spacer ahead: 160 bbl;

— volume of spacer behind to balance the plug: 26 bbl;

— total volume of spacer: 186 bbl;

— displacement volume to balance the plug: 448 bbl without under-displacement.

Cement and spacer are placed in the wellbore at the following depth:

— top of cement inside 16 in. casing: 15,420 ft;

— top of balanced cement with the workstring in place: 15,379 ft;

— top of balanced spacer with the workstring in place: 14,463 ft;

— top of spacer with the workstring out: 14,545 ft.

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