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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, and prevention of unintended cross flow. Topics discussed include cementing practices and the placement of well barrier elements. 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.

Shall: As used in a standard, “shall” denotes a minimum requirement in order to conform to the recommended practice.

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Wellbore Plugging and Abandonment

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. Wells temporarily abandoned (suspended) have intent to re-enter 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 useable water sources;
- above or below hydrocarbon bearing zones or other potential flow zones;
- at the surface or mudline.

See Figure 1 for an abandoned wellbore example.
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 surface plug.

Figure 1—Example Schematic of a Permanent Well Abandonment

2 Normative References

The following referenced documents are 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).


3 Terms, Definitions, 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 contributes to the total system reliability by preventing liquid or gas flow if properly installed.

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

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 suitable qualified materials.

3.1.4 cement sheath
The set cement in a given annulus between the borehole and tubulars or between tubulars.

3.1.5 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.

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

3.1.7 Inside Blow Out Preventer
IBOP
A tool used as a check valve inside the workstring.

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

3.1.9 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 element.

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

3.1.10 plug
A verifiable barrier element located within the wellbore which may be mechanical or cement.
3.1.11 retainer
A mechanical device, usually equipped with elastomer elements that allows passage of cement that can then be closed and act as a permanent barrier element.

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

3.1.12 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.

3.1.13 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 Abbreviations
For the purpose of this document, the following acronyms are used:

BHA bottom hole assembly
CBL cement bond log
ECD equivalent circulating density
IBOP inside blow out preventer
NAF non-aqueous fluid
VDL variable density log
SCP sustained casing pressure

4 Applications and Operating Environment

4.1 Formation Types

4.1.1 Potential Flow Zones
Potential flow zones are any formation in a well where flow is possible when the wellbore pressure is less than the pore pressure (e.g. reservoir hydrocarbon zones, shallow gas, or over-pressurized water zones). 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 are 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 run-off.
4.1.3 Injection and Depleted Zones

Injection or disposal zones are geological formations whose strata is 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 formations 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 will prevent the flow of formation fluids to surface or seabed, cross flow between permeable formations, and contamination of useable water sources.

Since the initial geologic state was a continuous seal, this is typically performed by creating 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](image)

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. Guidance provided in API 65-2 shall be used for the evaluation of potential flow zones. Local regulatory authorities may define zones which 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 then 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.

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Considerations for the placement of permanent abandonment barriers can include:

- location of potential flow zones, and pore pressures;
- location of useable water sources;
- formation fracture pressure of natural seals;
4.2.3 Open Hole

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

Figure 4—Open Hole Abandonment by Balanced Plugs
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 5—Open Hole Abandonment with a Cement Retainer Set at Casing Shoe

Figure 6—Cased Hole Abandonment with a Perforation Squeeze and a Balanced Plug
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, mechanical plugging, and dump bailer.
4.2.6 Casing Stub or Liner Top

A casing stub or liner top can introduce a new flow path which 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 in order 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, mechanical plugging, and dump bailer.

NOTE A bridge plug may or may not be feasible for this type abandonment.
4.2.7 Useable Water Sources

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

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

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 being landed on the previous 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

There are several materials available for consideration in the design of a barrier. Materials, in this document, can be classified as either chemical, natural and induced, 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 where it will be placed.

The materials compromising the barrier construction, whether stand-alone or part of a composite 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;
— 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 permanent barrier.

If adequate information cannot be obtained from historical data, additional lab 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 standard.

5.1 Environment

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

— temperature and pressure;
— chemical exposure;
— anticipated well events after placement.

5.1.1 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 will provide the required properties to achieve successful placement in the well and long-term sealing properties required for well abandonment. Portland cement is typically the material of choice for well abandonment operations as it can
be easily engineered to achieve successful placement in the well and it has been proven to provide long-term sealing integrity for barrier construction. See 5.1.3 for more detail on after placement considerations of temperature and pressure.

5.1.2 Chemical Exposure

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

5.1.3 Well Events after Placement

Anticipated well events after placement should be considered when selecting materials for barrier construction. The most common well events involve temperature and pressure changes.

Pressure changes are created by fluid densities in the well, whether planned or unforeseen, that may impact the pressure differential across the placed barrier. Examples of pressure changes include nitrogen lifting, fluid swaps, fluid influxes, positive or negative tests, injection, depletion, formation movement, or production.

Temperature changes after placement related to, or independent of the pressure affects, are another important design consideration when selecting materials. The most common temperature changes occur during well stimulation, production, shut-in, and well killing operations.

5.2 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 geopolymers. 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, and expanding agents, etc.).

5.3 Natural and Induced

5.3.1 Collapsible Formations

In certain geologic settings, annular isolation may be established by post-drilling formation movement. Most typically, formations 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). To serve as a natural annular barrier a formation should have sufficient strength to withstand the maximum anticipated pressure to which it will be exposed 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.

5.3.2 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 cement sheath evaluation logging (cement bond log (CBL)/variable density log (VDL), Ultrasonic, etc.) 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 sheath 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 sheath evaluation log output parameters such as CBL pipe amplitude values, VDL signature, acoustic impedance/attenuation measurements/maps, etc. are then cataloged for the candidate natural annular barrier interval. If the initial log measurements indicate 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 single set of perforations in the middle of the candidate interval may be considered provided surface monitoring of the annulus can verify any pressure communication.

Once confidence is established in the cement sheath evaluation log acceptance criteria and pressure testing results, the standalone logging results may be used to qualify the natural annular barrier.

5.3.3 Degraded Drilling Mud

Over time a static drilling 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 5.3.2 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 composite system to meet the barrier requirements.

5.4 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.

The sealing capability prevents the flow of fluid through the barrier material or along the sealing interface. The barrier material is required to be effectively placed in the well at the correct position, and then maintain its position. The durability of the barrier material allows the barrier to maintain its characteristics for the planned service life.

Mechanical plugs are typically used as a reliable base for cement which is placed above the mechanical plug. They aide 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 are 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 mechanical barrier.
6 Installation

6.1 Placement Methods

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 is calculated 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 impact 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

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 hydrostatically balanced. 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.

Additional placement methods include pump-and-pull, inside blow out preventer (IBOP), and sacrificial workstring releasing tools.

6.1.4.2 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 hole. This method does not rely on hydrostatic forces to balance the cement plug.

This method of placement may have the following advantages:

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

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

— reduce equivalent circulating densities (ECDs) during placement.

This method of placement may have the following disadvantages:

— more involved calculations than conventional balanced plugs when coordinating pumping rate to pull out of hole speed;

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

— connections can be wet.

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

Figure 14—Example of a Pump and Pull Procedure

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 100 ft (30 m) to 300 ft (90 m) 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 stinger, 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) the workstring is pulled out of hole and the cement at the top of the plug may become intermixed with the cement spacer or drilling fluid.

To prevent u-tubing or free fall of fluids during connections, the annular can be closed.

### 6.1.4.2.1 Perforation, Wash, and Cement

Perforation, wash and cement (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. < 0.75 in. (19 mm)) than those used for the jetting system which are usually 1 in. (25 mm) or larger in diameter. The cup type system is 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 typical perforation density for the cup type system is 12 shots/ft (39 shots/m) and for the jet type system is 18 shots/ft (59 shots/m).

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 drill pipe 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.

### 6.1.4.3 Inside Blow Out Preventer

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 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 will be pulled wet until 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:
6.1.4.3.1 Modified IBOP

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

6.1.4.4 Sacrificial Workstring

A sacrificial workstring (tailpipe) should be considered when short thickening times (i.e. thixotropic designs) are required or 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 which 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. Effective cement placement around the workstring should be considered when utilizing this method.

NOTE Thixotropic designs exhibit rapid gel strength development when static but when sheared, resumes fluid dynamics.

6.1.4.5 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, in which the squeeze pressure is controlled at the wellhead, may be used. Casing integrity should be considered before applying the bradenhead squeeze method.

6.1.4.6 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 performing a tubing punch (perforating), typically immediately 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.

![Figure 17—Through-Tubing Method Isolating a Potential Flow Zone](image)

Placement verification can be achieved by tagging and pressure testing of the plug. 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;
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— tubing and casing condition;
— evidence of sustained casing pressure (SCP);
— control lines.

6.1.4.7 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.

6.1.5 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 is 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 Best Practices

6.2.1 Balanced Plugs

6.2.1.1 Introduction

This section includes guidelines proven successful across the industry. Fundamental theory and principles are provided as well as emphasized, but allowances should be made for specific locations and wellbore conditions 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 an unset plug. Sound engineering practices are required to ensure effective plug placement of the cement barrier.

6.2.1.2 Wellbore Preparation

The mud may have density and viscosity variations within the wellbore and active system. It is important to condition the hole ensuring the mud is homogeneous and all cuttings, gelled mud and mud cake is removed, loosened, or minimized. A constant mud density throughout the wellbore is required for successfully setting a balanced plug. Furthermore, a proper mud circulation plan will result in stable circulating temperature and uniform viscosity for plug placement. The pre-job circulation plan should be dictated by the required rate and volume for hole cleaning. Respect should be given to well control at all times.

6.2.1.3 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 in order to achieve the desired length of a competent plug. When planning long cement plugs consider rig capability and the time required to pull out of the plug. Alternatively, the pump and pull technique should be considered for placement of longer cement plugs when a single long 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.

### 6.2.1.4 Cement Volume

The cement volume required 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 is 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.

### 6.2.1.5 Spacer Volume

The spacer volume ahead is typically sufficient to cover a minimum annular length of 500 ft (150 m). 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.

### 6.2.1.6 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;
- lab testing should verify the spacer is compatible with the mud and the cement;
- the spacer should be compatible with all formations it will contact;
- the spacer contains surfactants capable of providing preferential water wetting if non-aqueous fluid (NAF) is in the well.

Water can be used in lieu of weighted viscous spacer when the mud in the well is a clear fluid. Base oil is not recommended.

### 6.2.1.7 Cement 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 and/or high pressure environments. An expanding agent can be added to impart bulk expansion to the set cement. The addition of 35% silica for strength retrogression is required at bottomhole static temperature (BHST) greater than 230 °F (110 °C). The inclusion of salt in the cement may be warranted when cementing across salt formations. Shale inhibition can also be considered when appropriate.

### 6.2.1.8 Cement Density

The cement density should be higher than the mud density to achieve effective mud removal and maintain overbalance pressure. The cement density is usually dictated by the type of cement available.

If a suitable base is not available below the plug, consideration should be given to minimizing the density difference between the mud and the cement 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. This should minimize slumping at the top and the bottom of the plug.

6.2.1.9 Compressive Strength

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

6.2.1.10 Thickening Time

Thickening time should account for the placement time including the time to pull the workstring a minimum of 500 ft (150 m) above the top of the plug and a safety factor. Excessive thickening times will 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 temperature simulator is recommended if available.

6.2.1.11 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.

6.2.1.12 Fluid Loss

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

6.2.1.13 Plug Base

When placing a cement plug on top of a lighter density fluid, swapping due to buoyancy differences will occur. In cases where the plug will be set off-bottom a plug base may be necessary, 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.

6.2.1.13.1 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.

6.2.1.13.2 Viscous Reactive Pills

Viscous reactive pills (VRP) are effective in providing a base for cement plugs. These pills are placed with the top of the pill at the planned depth for the bottom of the cement plug. A pill length of 200 ft to 300 ft (60 m to 90 m) is recommended. Viscous reactive pills should be designed that when they come in contact with cement they react to form an immobile type mass. Sodium silicate and bentonite are commonly used to formulate a VRP. The risk of sticking the workstring should be assessed, especially when using VRP in high angle holes.

When setting plugs in high bentonite water-based mud, a VRP may not be required as the cement will react with the bentonite in the drilling fluid.
6.2.1.13.3 High Density Drilling Fluid

Filling the hole below the plug with drilling fluid having a density greater than or equal to the cement density will prevent fluid swapping.

6.2.1.14 Pipe Movement

Pipe movement by rotation and/or reciprocation should aid in good mud displacement during plug setting operations

6.2.1.14.1 Rotation

Rotation at the maximum r/min attainable within torque limits should aid in fluid displacement. Rotation has shown to be more effective for mud displacement than reciprocation.

6.2.1.14.2 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 will result in intermixing and contamination of the spacer with mud and the cement with spacer and mud.

6.2.1.15 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, place one wiping device between the mud and the spacer ahead of the cement and another wiping device 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 are not recommended. Once the workstring is above the top of the plug, pumping a wiping device can help clean the inside of the workstring.

Open cell foam balls are effective for both fluid separation and cleaning the workstring. Standard wiper darts can also be used but their wiping efficiency may not be as effective.

Wiper plugs and balls can be used with a plug catcher to indicate when the cement is in place and to prevent overdisplacement.

Use a suitable launching device to prevent prolonged shutdowns while launching balls or darts.

6.2.1.16 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 will prevent 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 confirm there is sufficient space to catch them at the diverter without blocking the openings. Check the foam balls can be extruded through the diverter openings.

6.2.1.17 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 prevent disturbance while pulling out of the plug.

### Table 1—Reduced Diameter Stinger Selection

<table>
<thead>
<tr>
<th>Open Hole/Casing Diameter (in. (mm))</th>
<th>Stinger Diameter (in. (mm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.50 (&lt; 216)</td>
<td>2.375 to 3.500 (60 to 89)</td>
</tr>
<tr>
<td>8.50 to 12.25 (216 to 311)</td>
<td>3.500 to 4.500 (89 to 114)</td>
</tr>
<tr>
<td>12.25 to 14.00 (311 to 356)</td>
<td>4.500 to 5.875 (114 to 149)</td>
</tr>
<tr>
<td>14.00 to 17.50 (356 to 445)</td>
<td>5.875 to 6.625 (149 to 168)</td>
</tr>
<tr>
<td>17.50 (&gt; 445)</td>
<td>6.625 (168)</td>
</tr>
</tbody>
</table>

The stinger 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 may cause the initially balanced plug to unbalance while pulling out of it. This can lead to cement contamination as well as pulling wet.

Using a reduced diameter stinger may prevent the use of wiper darts. Use foam wiper balls to overcome this limitation.

### 6.2.1.18 Displacement

To ensure accurate control over displacement volume, use the cement unit for displacement. The pump rate should be slowed down in the range of 1 bbl/min to 2 bbl/min (0.16 m³/min to 0.32 m³/min) for the last 5 bbl to 10 bbl (0.80 m³ to 1.60 m³) of displacement. For large displacement volumes, consider displacing with the rig. When using the rig, ensure crosschecking is possible between the fluid pulled from the mud system and the physical measurement. The plug should be underdisplaced to allow the cement to fall to the balance point and to pull the workstring dry.

Account for any compressibility of the mud in the displacement volume calculations. If this is not considered, there may be unintended additional underdisplacement 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.

### 6.2.1.19 Pulling and Circulating Guidelines

Pull the workstring out of the plug slowly to minimize disturbance of the plug. Pull up at least 500 ft (150 m) 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.

### 6.2.1.20 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 underdisplaced and pumping while pulling may be required.

7 Evaluation and Verification Criteria

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.

7.1 Annulus

Annular barriers may include cement, packers, collapsible formations, degraded drilling mud or combinations thereof. Evaluation of annular barriers should be performed using the methods as specified in API 10TR1.

7.1.1 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 will 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 will 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 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 indicates the location of the cement.

NOTE 3 Also called a job signature.

7.1.2 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 Inside Pipe (In-Pipe)

7.2.1 Physical or Mechanical Tests

Applying weight to a plug, also called tagging the plug, is a common method of verifying the plug depth in addition to confirming the plug will withstand 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 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 compressive 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.

7.2.1.1 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 will depend on the workstring and any regulatory requirements. A tally of the workstring in the hole when the plug is tagged will 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 will verify the plug setting depth. After setting and releasing the mechanical plug, it may be weight tested to verify it is properly set.

7.2.1.2 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 to using a workstring.

7.2.2 Hydraulic Tests

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.

7.2.2.1 Positive

Fluid is 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.

7.2.2.2 Inflow

After isolating the plug (e.g. with a retrievable packer), the hydrostatic pressure in the well is reduced until the pressure above the plug is less than the pore pressure of the zone(s) isolated by the plug. The well is monitored to verify it is stable and there is no flow. Inflow testing is also referred to as negative pressure testing.
Annex A  
(informative)

Balanced Plug Calculations

A.1 Multiple Workstrings and Annular Configurations

This procedure is an example of one method used to calculate a balanced cement plug with multiple workstrings and annular configurations. The following procedure will determine how to calculate a 1000 ft balanced cement plug with 160 bbl of weighted spacer ahead for the given wellbore shown in Figure A.1:

- 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

Please note Figure A.1 is not to scale.

![Figure A.1](image_url)

See Table A.1 for the workstring, casing, and open hole capacities.
Table A.1 Example Wellbore Capacities for Calculations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Depth (ft)</th>
<th>Length (ft)</th>
<th>Capacity (bb/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-5/8 in. 34 lb/ft drill pipe (DP)</td>
<td>5100</td>
<td>5100</td>
<td>0.02905</td>
</tr>
<tr>
<td>6-5/8 in. 27 lb/ft drill pipe 1 (DP1)</td>
<td>11,372</td>
<td>6272</td>
<td>0.03180</td>
</tr>
<tr>
<td>6-5/8 in. 27 lb/ft drill pipe 2 (DP2)</td>
<td>14,920</td>
<td>3548</td>
<td>0.03238</td>
</tr>
<tr>
<td>5-7/8 in. 23.4 lb/ft drill pipe</td>
<td>16,420</td>
<td>1500</td>
<td>0.02510</td>
</tr>
<tr>
<td>16 in. 109.6 lb/ft casing</td>
<td>16,291</td>
<td>-</td>
<td>0.21281</td>
</tr>
<tr>
<td>19.0 in. open hole (OH)</td>
<td>16,327</td>
<td>36</td>
<td>0.35069</td>
</tr>
<tr>
<td>16.5 in. open hole (OH)</td>
<td>16,420</td>
<td>93</td>
<td>0.26447</td>
</tr>
<tr>
<td>5-7/8 in. drill pipe x 16.5 in. open hole</td>
<td>-</td>
<td>93</td>
<td>0.23094</td>
</tr>
<tr>
<td>5-7/8 in. drill pipe x 19.0 in. open hole</td>
<td>-</td>
<td>36</td>
<td>0.31716</td>
</tr>
<tr>
<td>5-7/8 in. drill pipe x 16 in. casing</td>
<td>-</td>
<td>1371</td>
<td>0.17928</td>
</tr>
<tr>
<td>6-5/8 in. DP2 x 16 in. casing</td>
<td>-</td>
<td>3548</td>
<td>0.17018</td>
</tr>
</tbody>
</table>

A.1.1 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 ($V_{TP}$).

The total cement volume will be the summation of the individual calculation volumes. See Equations A.1 to A.4.
\[ V_{TP} = V_1 + V_2 + V_3 \]  

(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

\[ V_1 = (D_0 - D_1) \times C_1 \]  

(A.2)

\[ V_2 = (D_0 - D_1) \times C_2 \]  

(A.3)

\[ V_3 = (D_0 - D_1) \times C_3 \]  

(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

\[ V_1 = (16,420 - 16327) \times 0.26447 = 24.59 \text{ bbl} \]

\[ V_2 = (16,327 - 16291) \times 0.35069 = 12.62 \text{ bbl} \]

\[ V_3 = (16,291 - 15420) \times 0.21281 = 185.36 \text{ bbl} \]

and

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

**A.1.2 Top of Cement with the Workstring In**

Find the top of cement for the 1000 ft cement plug, with the workstring in, calculated according to A.1.1. Figure A.3 demonstrates the individual calculation volumes to determine the top of cement volume \( D_{cw,i} \).
Using the total cement volume required for the plug with the workstring out ($V_{TP}$), fill up the pairing calculation volumes ($V_5$ to $V_4$, $V_6$ to $V_7$, $V_9$ to $V_8$) 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.10.

\[
\begin{align*}
V_4 &= (D_0 - D_1) \times C_4 \\
V_5 &= (D_0 - D_1) \times C_5 \\
V_6 &= (D_0 - D_1) \times C_6 \\
V_7 &= (D_0 - D_1) \times C_7 \\
V_8 &= (D_0 - D_1) \times C_8 \\
V_9 &= (D_0 - D_1) \times C_9
\end{align*}
\] (A.5) (A.6) (A.7) (A.8) (A.9) (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 across 16.5 in. open hole, expressed in bbl/ft;
There are five capacity parameters:

- $C_5$ is the capacity of a 5-7/8 in. by 16.5 in. configuration, expressed in bbl/ft;
- $C_6$ is the capacity of a 5-7/8 in. by 19.0 in. configuration, expressed in bbl/ft;
- $C_7$ is the capacity of a 5-7/8 in. workstring across 19.0 in. open hole, expressed in bbl/ft;
- $C_8$ is the capacity of a 5-7/8 in. workstring across 16 in. casing, expressed in bbl/ft;
- $C_9$ is the capacity of a 5-7/8 in. by 16 in. casing configuration, expressed in bbl/ft.

Therefore, calculate the first pairing volume:

$$ PV_1 = V_4 + V_5 $$

where:

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

Thus,

$$ V_4 = (16,420 - 16327) \times 0.02510 = 2.33 \text{ bbl} $$

$$ V_5 = (16,420 - 16327) \times 0.23094 = 21.47 \text{ bbl} $$

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

As 23.8 bbl is less than $V_{TP}$, continue to the next pairing volume:

$$ PV_2 = V_6 + V_7 $$

where:

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

Thus,

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

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

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

As 36.12 bbl is less than $V_{TP}$, continue to the next pairing volume:

$$ PV_3 = V_8 + V_9 $$

where:

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

Thus,

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

$$ V_9 = (16,291 - 14,290) \times 0.17928 = 358.74 \text{ bbl} $$
as 445.09 bbl is greater than $V_{TP}$, determine the height of cement across $PV_3$. The total plug volume remaining is 186.46 bbl. This volume has to be balanced across $PV_3$. Therefore, Equation A.13 becomes:

$$PV_3 = V_8 + V_9 = 186.46 \text{ bbl} \tag{A.14}$$

and

$$\frac{V_8}{C_8} = \frac{V_9}{C_9} \tag{A.15}$$

or

$$V_8 * C_9 = V_9 * C_8 \tag{A.16}$$

substituting Equation A.14 into Equation A.16:

$$V_8 * C_9 = (186.46 - V_8) * C_8 \tag{A.17}$$

so solving for $V_8$:

$$V_8 C_9 = 186.46 C_8 - V_8 C_8$$

$$V_8 C_9 + V_8 C_8 = 186.46 C_8$$

$$V_8 (C_9 + C_8) = 186.46 C_8$$

$$V_8 (0.17928 + 0.02510) = 186.46 \times 0.02510$$

$$V_8 = 22.89 \text{ bbl}$$

and for $V_9$:

$$186.46 = 22.89 + V_9$$

$$V_9 = 163.56 \text{ bbl}$$

With the pairing volumes are equal, the heights are determined according to Equation A.15:

$$H_8 = \frac{V_8}{C_8} \tag{A.18}$$

$$H_9 = \frac{V_9}{C_9} \tag{A.19}$$

where:

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

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

so

$$H_8 = 22.89/0.02510 = 911.95 \text{ ft}$$
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 $H_9$.

$$D_{c-wsi} = 16,291 - 912 = 15,379 \text{ ft}$$

where:

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

**A.1.3 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.1.1 using a spacer volume ahead of 160 bbl. Same approach as the requirements given in A.1.2 is followed to determine which pairing volumes will remain partially filled with the 160 bbl of spacer volume ahead ($V_{sa}$).

Using the top of cement with the workstring in ($D_{c-wsi}$), determined as specified in A.1.2, calculate the top (depth) of the spacer ahead in the annulus. Compare this against $V_9$.

From Equation A.10,

$$D_1 = D_{c-wsi} - \frac{V_{sa}}{C_9}$$

$$D_1 = 15,379 - (160/0.17928)$$

$$D_1 = 14,486.54 \text{ ft}$$

Comparing the ending depth of 6-5/8 in. DP2 of 14,920 ft to the depth of 14,486.54 ft, indicates the top of the spacer ahead will be in the next pairing volume ($V_{10}$ to $V_{11}$). 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

As PV3 was partially filled according to A.1.2 and it was determined above the volume of spacer ahead fills the remaining annular volume \( V_9 \), the difference that will consume \( V_{10} \) is calculated.

The volume of the spacer ahead consumed in \( V_9 \) is the difference from \( D_{c-wsi} \) and \( D_1 \) for PV3. Using Equation A.10,

\[
V_{9R} = (D_{c-wsi} - D_1) \times C_9
\]  
(A.20)

where:

\( V_{9R} \) is the volume remaining in \( V_9 \), expressed in bbl;

thus

\[
V_{9R} = (15,379 - 14,920) \times 0.17928 \\
V_{9R} = 82.28 \text{ bbl}
\]

As the total volume of spacer ahead (\( V_{sa} \)) is 160 bbl, the annular volume remaining (\( V_{10R} \)) in the next pairing volume (PV4) is 77.72 bbl. From \( V_{10R} \), the balanced volume of spacer behind is determined in PV4. Determine the annular height of \( V_{10R} \) using Equation A.21, which is similar to Equation A.18:

\[
H_{10} = \frac{V_{10R}}{C_{10}}
\]  
(A.21)

where:

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

\( C_{10} \) is the capacity of the 6-5/8 in. DP2 by 16 in. configuration, expressed in bbl/ft;

\( V_{10R} \) is the remaining spacer volume the 6-5/8 in. DP2 by 16 in. configuration, expressed in bbl;

thus

\[
H_{10} = (77.72/0.17018) \\
H_{10} = 457 \text{ ft}
\]

To balance the spacer behind in PV4, the height in the annulus (\( H_{11} \)) equals the height inside the 6-5/8 in. DP2 workstring (\( H_{11} \)). Applying this to Equation A.21,

\[
H_{11} \times C_{11} = V_{11S}
\]  
(A.22)

where:

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

\( C_{11} \) 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
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\[ V_{11S} = 457 \times 0.03238 \]
\[ V_{11S} = 14.79 \text{ bbl} \]

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

Using the top of cement with the workstring in (\( D_{c-wsi} \)), determined according to A.1.2 and using Equation A.20,

\[ V_{br} = (D_{c-wsi} - D_1) \times C_8 \]

(A.23)

where:

\( V_{br} \) is the volume remaining in \( V_b \), expressed in bbl;

thus

\[ V_{br} = (15,379 - 14,920) \times 0.02510 \]
\[ V_{br} = 11.52 \text{ bbl} \]

Therefore the total volume of spacer behind is

\[ V_{sb} = V_{br} + V_{11S} \]

(A.24)

where:

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

thus

\[ V_{sb} = 11.52 + 14.79 \]
\[ V_{sb} = 26.31 \text{ bbl} \]

A.1.4 Top of Spacer with the Workstring In

To determine the top of the spacer with the workstring in (\( D_{s-wsi} \)), since the height of the spacer consumed inside \( V_{tr} \) is known from \( H_{tr} \) as specified in Equation A.22, the difference is taken between the bottom depth of the pairing volumes (\( PV_4 \)) and \( H_{tr} \).

\[ H_{11} = (D_0 - D_{s-wsi}) \]

(A.25)

where:

\( D_{s-wsi} \) is the top depth of the spacer in either volume segment, expressed in ft;

thus

\[ 457 = (14920 - D_{s-wsi}) \]
\[ D_{s-wsi} = (14920 - 457) \]
A.1.5 Top of Spacer with the Workstring Out

The total volume of spacer 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](image)

Using Equation A.4, $V_{12}$ becomes:

$$V_{12} = (D_0 - D_{s-wso}) \times C_3$$  \hspace{1cm} (A.26)

where:

- $V_{12}$ is the spacer volume inside the 16 in. casing, expressed in bbl;
- $D_{s-wso}$ is the top depth of the spacer volume inside the 16 in. casing, expressed in ft;

thus:

$$D_0 - \frac{V_{12}}{C_3} = D_{s-wso}$$

$$D_{s-wso} = 15,420 - \frac{186.3}{0.21281}$$

$$D_{s-wso} = 14,544 \text{ ft}$$

A.1.6 Displacement Volume to Balance the Plug
The displacement volume ($V_{d}$) to balance the plug would be the inside volume of the workstring to the top depth of the spacer determined according to A.1.5. To determine this volume, the remaining capacities in the workstring are calculated together. Figure A.6 illustrates the individual volume calculations.

The calculation volume in $V_{11}$ would be the remaining capacity ($V_{11R}$) since part is consumed with $V_{11S}$. Therefore applying Equation A.23:

$$V_{11R} = (D_{s-wsi} - D_1) * C_{11}$$  \hspace{1cm} (A.27)

where:

$D_{s-wsi}$ is the top depth of the spacer in either volume segment, expressed in ft;

$V_{11R}$ is the remaining spacer volume inside the 6-5/8 in. DP2 workstring, expressed in bbl;

thus

$$V_{11R} = (14,463 - 11,372) * 0.03238$$

$$V_{11R} = 100.08 \text{ bbl}$$

The next volume calculation is $V_{13}$; the capacity of the 6-5/8 in. DP1 workstring.

$$V_{13} = (D_0 - D_1) * C_{13}$$  \hspace{1cm} (A.28)

where:

$V_{13}$ is the volume inside the 6-5/8 in. DP1 workstring, expressed in bbl;

$C_{13}$ is the capacity of the 6-5/8 in. DP1 workstring, expressed in bbl/ft;

thus
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\[ V_{13} = (11,372 - 5100) \times 0.03180 \]
\[ V_{13} = 199.45 \text{ bbl} \]

The next volume calculation is \( V_{14} \); the capacity of the 6-5/8 in. 34 lb/ft workstring.

\[ V_{14} = (D_0 - D_1) \times C_{14} \quad (A.29) \]

where:

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

\( C_{14} \) is the capacity of the 6-5/8 in. 34 lb/ft workstring, expressed in bbl/ft;

thus

\[ V_{14} = (5100 - 0) \times 0.02905 \]
\[ V_{14} = 148.15 \text{ bbl} \]

Therefore the total displacement volume would be:

\[ V_{dt} = V_{14} + V_{13} + V_{11R} \quad (A.30) \]

where:

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

thus

\[ V_{dt} = 148.15 + 199.45 + 100.08 \]
\[ V_{dt} = 447.70 \text{ bbl} \]

A.2 Open Hole Balanced Plug with a Tailpipe

This procedure is an example of one method used to calculate a balanced cement plug using a tailpipe or stinger in the open hole. The following procedure will determine how to calculate a 7000 ft balanced cement plug with 75 bbl of weighted spacer ahead for the given wellbore as shown in Figure A.7:

- 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;
- displacement volume to balance the plug.
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Figure A.7—Example Wellbore with (a) Workstring Out and (b) Workstring In

See Table A.2 for the workstring, casing, and open hole capacities.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Depth (ft)</th>
<th>Length (ft)</th>
<th>Capacity (bbl/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-1/2 in. 16.6 lb/ft drill pipe (DP)</td>
<td>8500</td>
<td>8500</td>
<td>0.01422</td>
</tr>
<tr>
<td>2-7/8 in. 8.7 lb/ft tubing (TBG)</td>
<td>10,000</td>
<td>1500</td>
<td>0.00496</td>
</tr>
<tr>
<td>9-5/8 in. 53.5 lb/ft casing (CSG)</td>
<td>4000</td>
<td>4000</td>
<td>0.07076</td>
</tr>
<tr>
<td>9.0 in. open hole (OH)</td>
<td>10,000</td>
<td>6000</td>
<td>0.07868</td>
</tr>
<tr>
<td>2-7/8 in. TBG x 9 in. OH</td>
<td>-</td>
<td>1500</td>
<td>0.07065</td>
</tr>
<tr>
<td>4-1/2 in. DP x 9 in. OH</td>
<td>-</td>
<td>4500</td>
<td>0.05901</td>
</tr>
</tbody>
</table>

A.2.1 Total Cement Volume Required

Find the volume of cement required to set a 700 ft balanced plug on bottom, with no workstring in place. Figure A.8 demonstrates the individual calculation volumes to determine the total volume ($V_{TP}$).
The total cement volume will be the individual calculation volume ($V_1$) as specified in Equation A.31.

$$V_1 = (D_0 - D_1) \times C_1$$  \hspace{1cm} \text{(A.31)}

where:
- $C_1$ is the capacity of the 9 in. open hole, expressed in bbl/ft;
- $V_1$ is the cement volume in the 9 in. open hole, expressed in bbl;

thus

$$V_1 = (10,000 - 9300) \times 0.07868$$

$$V_1 = 55.08 \text{ bbl}$$

**A.2.2 Top of Cement with the Workstring In**

Find the top of cement for the 700 ft cement plug, with the workstring in, calculated according to A.2.1. Figure A.9 demonstrates the individual calculation volumes to determine the top of cement volume ($D_{c-wsi}$).
Using the total cement volume required for the plug with the workstring out \( V_1 \) and equating that to the pairing calculation volume, \( PV_1 \), identify the height of the plug in \( V_2 \) and \( V_3 \). Therefore

\[
PV_1 = V_2 + V_3 = 55.08 \text{ bbl} \tag{A.32}
\]

where:

\( PV_1 \) is the pairing volume for the 9 in. open hole, expressed in bbl;

and

\[
V_2 = (D_0 - D_1) \times C_2 \tag{A.33}
\]
\[
V_3 = (D_0 - D_1) \times C_3 \tag{A.34}
\]

so

\[
\frac{V_2}{C_2} = \frac{V_3}{C_3} \tag{A.35}
\]

or

\[
V_2 \times C_3 = V_3 \times C_2 \tag{A.36}
\]

substituting Equation A.32 into Equation A.36:

\[
V_2 \times C_3 = (55.08 - V_2) \times C_2 \tag{A.37}
\]

so solving for \( V_2 \):

\[
V_2C_3 = 55.08C_2 - V_2C_2
\]
\[
V_2C_3 + V_2C_2 = 55.08C_2
\]
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\[ V_2 (C_3 + C_2) = 55.08C_2 \]
\[ V_2 (0.00496 + 0.07065) = 55.08 \times 0.07065 \]
\[ V_2 (0.07561) = 3.8914 \]
\[ V_2 = 51.47 \text{ bbl} \]

and for \( V_3 \):

\[ 55.08 = 51.47 + V_3 \]
\[ V_3 = 3.61 \text{ bbl} \]

Use either \( V_2 \) or \( V_3 \) to determine the height in the given configuration. Using Equation A.33:

\[ (10,000 - D_{c-wsi}) = \frac{51.47}{0.07065} \]
\[ D_{c-wsi} = 10,000 - 728.52 \]
\[ D_{c-wsi} = 9,271 \text{ ft} \]

### A.2.3 Volume of Spacer Behind to Balance the Plug

Find the volume of spacer behind (\( V_{sb} \)) to balance the 700 ft cement plug, with the workstring in, calculated as specified in A.2.1 using a spacer volume ahead of 75 bbl. Same approach according to A.2.2 is followed to determine which pairing volumes will remain partially filled with the 75 bbl of spacer volume ahead (\( V_{sa} \)).

Using the top of cement with the workstring in (\( D_{c-wsi} \)), determined according to A.2.2, calculate the top (depth) of the spacer ahead in the annulus. Compare this against \( V_2 \). See Figure A.10 with the individual calculation volumes to determine the volume of spacer behind to balance (\( V_{sb} \)).

![Figure A.10—Calculation Volumes for Spacer Behind with Workstring In](image)

From Equation A.33,
Comparing the ending depth of 4-1/2 in. DP of 8500 ft to the depth of 8209 ft, indicates the top of the spacer ahead will be in the next pairing volume (V4 to V5). Therefore, part of the spacer volume ahead will consume the remaining volume in V2 and the difference will partially fill V4. Once the partial fill volume is known, the equivalent height in V5 is calculated.

The volume of the spacer ahead consumed in V2 is the difference from \( D_{c-wsi} \) and \( D_1 \) for PV1. Using Equation A.33,

\[
V_{2R} = (D_{c-wsi} - D_1) \times C_2
\]  

(A.38)

where:

- \( V_{2R} \) is the volume remaining in V2, expressed in bbl;

thus

\[
V_{2R} = (9,271 - 8,500) \times 0.07065
\]

\[
V_{2R} = 54.47 \text{ bbl}
\]

As the total volume of spacer ahead (\( V_{sa} \)) is 75 bbl, the annular volume remaining (\( V_{4R} \)) in the next pairing volume (PV2) is 20.53 bbl. From \( V_{4R} \), the balanced volume of spacer behind is determined in PV2. Determine the annular height of \( V_{4R} \) using Equation A.39, which is similar to Equation A.35:

\[
H_4 = \frac{V_{4R}}{C_4}
\]  

(A.39)

where:

- \( H_4 \) is the height inside the 4-1/2 in. DP by 9 in. configuration, expressed in ft;
- \( C_4 \) is the capacity of the 4-1/2 in. DP by 9 in. configuration, expressed in bbl/ft;
- \( V_{4R} \) is the remaining spacer volume in the 4-1/2 in. DP by 9 in. configuration, expressed in bbl;

thus

\[
H_4 = (20.53/0.05901)
\]

\[
H_4 = 347 \text{ ft}
\]

To balance the spacer behind in PV2, the height in the annulus (\( H_5 \)) equals the height inside the 4-1/2 in. DP workstring (\( H_5 \)). Applying this to Equation A.39,

\[
H_5 \times C_5 = V_{5S}
\]  

(A.40)

where:
$H_5$ is the height inside the 4-1/2 in. DP workstring, expressed in ft;
$C_5$ is the capacity of the 4-1/2 in. DP workstring, expressed in bbl/ft;
$V_{ss}$ is the balanced spacer volume behind in 4-1/2 in. DP workstring, expressed in bbl;

thus

\[ V_{ss} = 347 \times 0.01422 \]
\[ V_{ss} = 4.94 \text{ bbl} \]

Since it was established $PV_1$ is filled due to $V_{sa}$, the corresponding volume remaining inside the 2-7/8 in. workstring to be consumed needs to be determined ($V_{3R}$).

Using the top of cement with the workstring in ($D_{c-wsi}$), determined according to A.2.2 and using Equation A.34,

\[ V_{3R} = (D_{c-wsi} - D_1) \times C_3 \]  (A.41)

where:

$V_{3R}$ is the volume remaining in $V_3$, expressed in bbl;

thus

\[ V_{3R} = (9,241 - 8,500) \times 0.00496 \]
\[ V_{3R} = 3.67 \text{ bbl} \]

Therefore the total volume of spacer behind is

\[ V_{sb} = V_{3R} + V_{ss} \]  (A.42)

where:

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

thus

\[ V_{sb} = 3.67 + 4.94 \]
\[ V_{sb} = 8.61 \text{ bbl} \]

A.2.4 Displacement Volume to Balance the Plug

The displacement volume ($V_{ds}$) to balance the plug would be the inside volume of the workstring to the top depth of the spacer determined as specified in A.2.3. To determine this volume, the remaining capacity in the 4-1/2 in. DP workstring is calculated.

First, calculate the top of the spacer with the workstring in ($D_{s-wsi}$), since the height of the spacer consumed inside $V_5$ is known from $H_5$ according to Equation A.40, the difference is taken between the bottom depth of the pairing volumes ($PV_2$) and $H_5$.

\[ H_5 = (D_0 - D_{s-wsi}) \]  (A.43)
where:

\( D_{s-wsi} \) is the top depth of the spacer in the volume segment, expressed in ft;

thus

\[
347 = (8,500 - D_{s-wsi})
\]

\[
D_{s-wst} = (8,500 - 347)
\]

\[
D_{s-wst} = 8,153 \text{ ft}
\]

Knowing the remaining volume is contained to the 4-1/2 in. DP workstring, use Equation A.40 to directly calculate the displacement volume.

\[
V_{dt} = (D_{s-wsi} - D_1) * C_5
\]  \hfill (A.44)

where:

\( V_{dt} \) is the displacement volume, expressed in bbl;

thus

\[
V_{dt} = (8,153 - 0) * 0.01422
\]

\[
V_{dt} = 115.9 \text{ bbl}
\]
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