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Implementation of a New Methodology for Efficient Well Abandonment Operations

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Abstract

Plugging and abandonment operations may require multiple cement plugs to isolate a given wellbore from the surface or seabed. The rig operational time placing and then validating the integrity of selective cement plugs could range from a couple of days to one week depending on the quantity and location of the plugs in the wellbore. As most plugs lengths target 500 feet, wellbore abandonment operations can become inefficient depending on the abandonment requirements. A new methodology for cement plug installation, during wellbore abandonment operations, using a drilling rig improves efficiency by reducing the quantity of cement plugs deployed while obtaining better placement success.

The methodology, a "pump and pull" technique, has enabled successful plug placements range from a 1,650-foot plug set in a highly deviated well to a 1,950-foot plug set in a vertical well. Most of these placements enabled a reduction in the plugs required to achieve the abandonment objectives. The manuscript discusses the general operational procedures, laboratory testing, and design methods to manage the deployment scope using drilling rigs without coiled tubing assistance.

Introduction

Wellbore abandonment requirements continue to evolve in response to greater awareness of potential environmental risks and industry lessons learned. As a result, there have been efforts to support improved abandonment requirements with the goal of restoring the well as close to the original condition prior to well construction. The knowledge of the potential flow zones in a given wellbore, with their ability for fluid migration, and any aquifers contamination risk resulting from the potential flow zones usually dictates the degree of isolation required.

With current wellbore abandonment practices, depending on the plug length used for isolation, achieving the objectives may require multiple plugs ranging from six up to sometimes twelve across a wellbore. A common plug length used for isolation across the industry generally targets 500 feet. This can be, as an example, dependent upon the wells geographical location, respective governing requirements, potential flow zone, and aquifer positions. Independent of the well utility and the abandonment scope, requiring temporary or permanent status, the plug placement success may influence the degree of isolation achieved. Reducing the number of plugs to achieve the abandonment objectives should help minimize this risk.

Portland cement is the industry-preferred material used for isolation during wellbore abandonment in comparison to alternative materials. The main advantages of using Portland cement are the overall cost, cement removal efficiency, and greater design freedom for downhole conditions.

Utilizing the pump and pull technique enables execution of longer cement plugs which should reduce the number of plugs deployed to achieve the abandonment requirements. The practice of pump and pull helps with the plug contamination risk compared to conventional balanced plug displacements, which can improve the degree of isolation achieved, especially in highly deviated and horizontal wells.

General Well Abandonment Using Cement Plugs

In general, wellbore abandonments objectives tend to focus on protecting aquifers from contamination, avoiding inter-zonal communication, and isolation of the wellbore from the surface or seabed. To achieve these type of objectives, the use of cement plugs for isolation provides an economic means making it a common deployment practice. Though not shown, close-ended mechanical plugs provide additional cement plug support and are usually included cement plug-based abandonments. Applying this to a general vertical wellbore with potential flow zones and aquifers, a cement plug based abandonment may look similar to Figure 1.

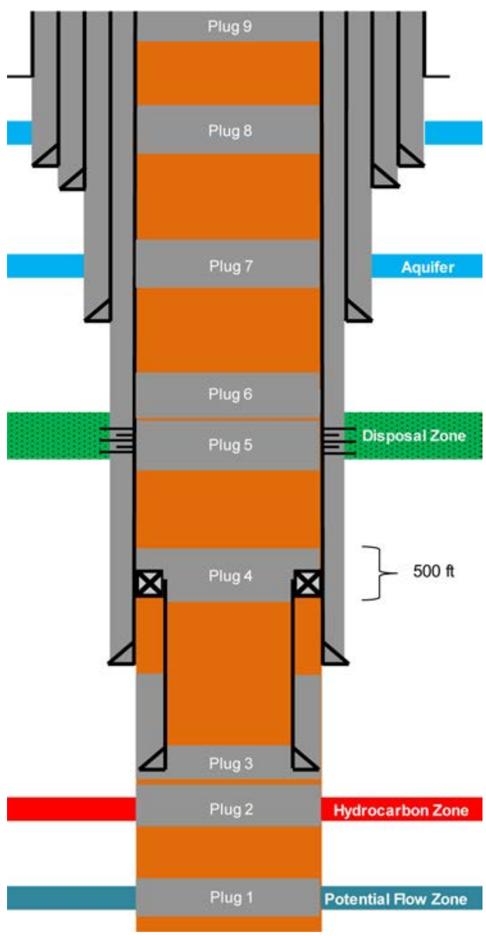

Figure 1—General well abandonment using cement plugs (vertical case)

For cases where the same wellbore has a highly deviated or horizontal section, a general abandonment using cement plugs may look similar to Figure 2. With limited industry guidance available on isolation requirements when the potential flow zones and aquifers are located in the highly deviated and horizontal sections of the wellbore, a common practice used is setting multiple series of cement plugs every thousand feet or a given interval depending on the vertical departure length. This enables a series of plug sets providing a contingency helping ensure these sections of the wellbore maintain isolation.

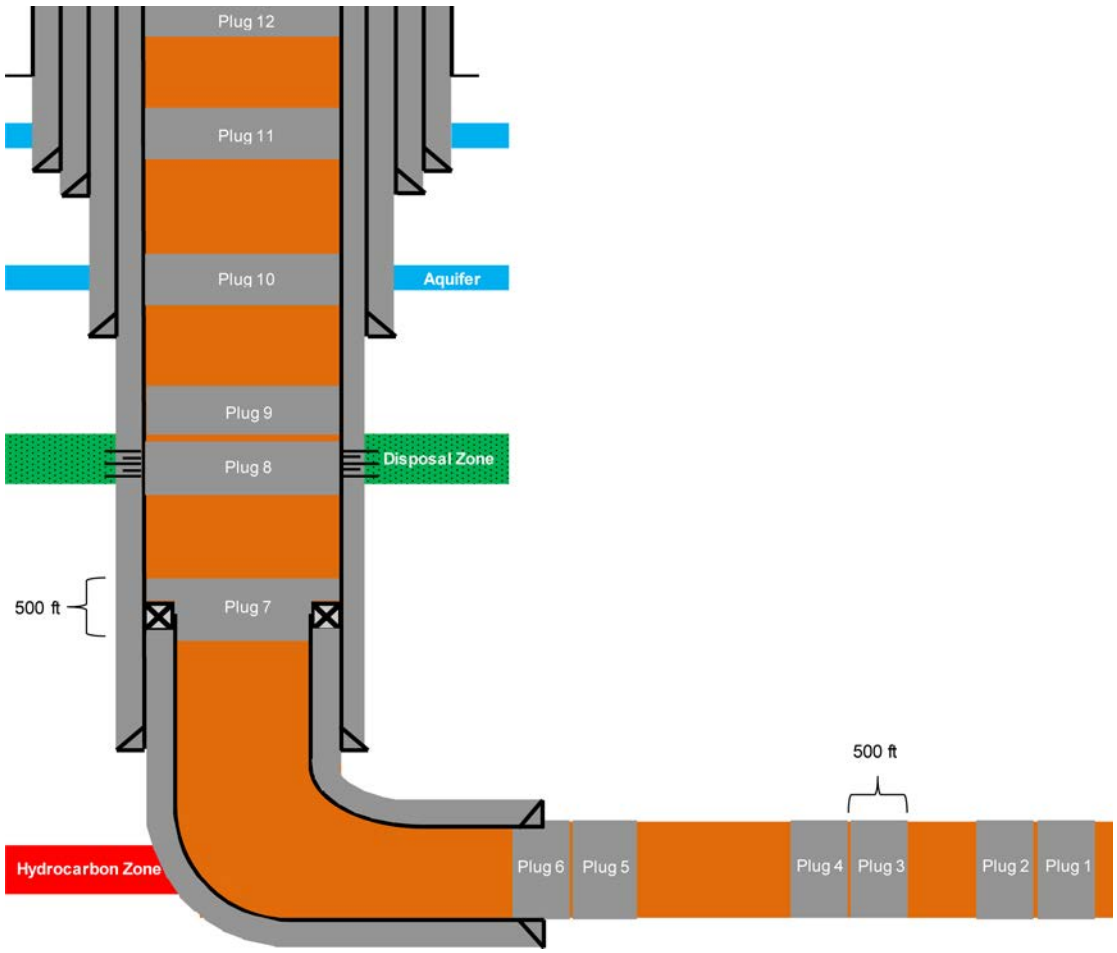

Figure 2—General well abandonment using cement plugs (horizontal case)

Depending on the abandonment objectives, some of the cement plugs will require integrity testing to confirm isolation. Integrity testing can vary across the industry though commonly it consist three parts after completion of the required wait on cement time. The first part is a "tag" or physical test at the top of the plug using a chosen applied weight. The next part is a positive pressure test that applies an additional hydrostatic pressure to the current wellbore fluid on top of the plug. The last part is a negative or "in-flow" test whereby the workstring submerged in the current wellbore fluid may be displaced with a lighter fluid inside the workstring to achieve a given pressure reduction.

For a single plug, the time to complete the integrity testing is reasonable. If a zone extends greater than 500 feet, requiring more than one 500-foot plug, the additional wait on cement time and integrity testing time can become inefficient. Similarly, in the highly deviated or horizontal sections, setting multiple plug sets to abandon the wellbore adds more operational time in addition to the integrity testing of the uppermost plug in the plug set.

Pump and Pull Technique

The pump and pull technique is an established practice for spotting fluids using coiled tubing. Similarly during drilling operations, when wellbore instability arises that require pumping cementing fluids for remediation, this same technique has shown good results using either a bottom-hole assembly or another form of workstring. However omitting this practice for routine plug placement using a drilling rig can be common. This usually stems from gaps in direct deployment experience on the rig as well as the knowledge of the associated procedures.

Normally, this practice involves simultaneously surface pumping fluids at the same equivalent downhole annular rate of the pull or tripping speed attempting to maintain a fixed fluid annular height behind the workstring during placement. The procedure and calculations to perform the pump and pull with coiled tubing can be straightforward. However, when applying this placement practice to using the drilling rig, procedure, and calculations become more complicated. The greatest operational difference is the start/stop sequence of pulling or tripping workstring stands while pumping with the rig.

During this sequence, each three joint (drill-pipe) stand disconnects from the top drive after removal from the well, racked into the derrick, and then the top drive reconnects to the next stand at the rig floor. This resumes until completing the required number of stands. To minimize the free-fall affect, as the initial annular fluid position is important for the pump and pull to balance the plug successfully, the backside or annulus is open and closed at various stages during the placement. When the backside is closed, circulation resumes through the choke and/or kill lines. Refer to Figure 3 for more details. See Appendix A for general planning calculations and Appendix B for a general placement procedure.

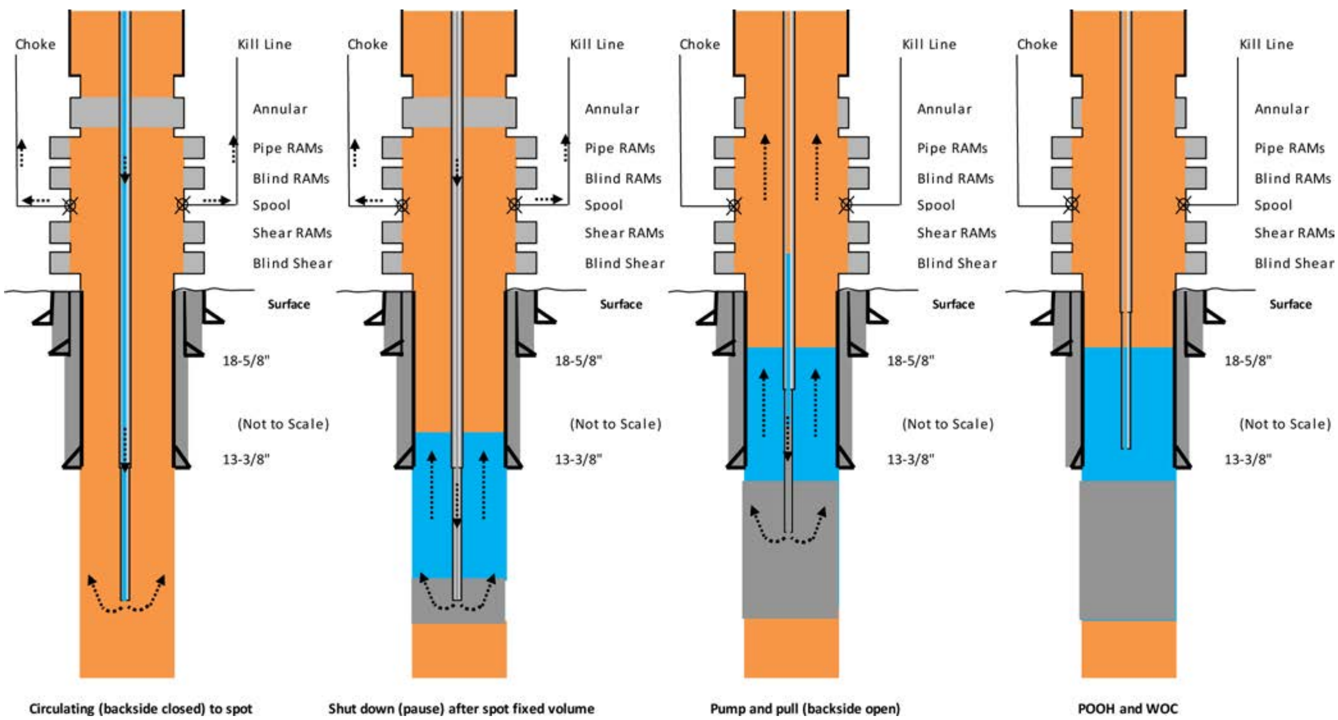

Figure 3—General illustration of the pump and pull technique

With the start/stop sequence, the pump and pull technique enables placement of cement plugs with lengths greater than 500 feet with less risk than using the conventional balanced plug displacement method.

New Methodology for Wellbore Abandonment

There are several differences with the pump and pull technique in comparison to a conventional balanced plug displacement method as shown in Table 1.

Table 1—Differences between placement methods

Pump and Pull	Conventional Displacement
Dynamic workstring and cement placement	Static workstring and dynamic cement placement
After installation, have to pull through a partial plug	After installation, have to pull through entire plug
Pressure pumps the balanced plug into place	Hydrostatically balances the cement plug

The greatest risk of using the displacement method, when spotting cement plugs, is the annular length of cement that remains static behind the workstring while the pulling through the plug after placement. Cement designs can have a tendency for gel strength development once in a static state. This behavior can accelerate with contamination or other downhole conditions not accounted for. As this risk increases with increased plug length, there can be hesitation to perform cement plugs with lengths greater than 500 feet. An alternative to this risk would be to minimize the static time and the annular length of cement behind the workstring which the pump and pull method accounts for.

Another placement factor, which can be challenging, is fluid displacement efficiencies. Fluid displacement efficiencies or minimizing the cement contamination during placement success can be highly dependent upon the annular configuration. As most plug placements tend to have large annular configurations, the cement plug integrity after installation can be difficult to quantify. Applying this to highly deviated and horizontal sections, the placement factor becomes more challenging since there is a change in the success criteria for fluid displacement mechanics. The pump and pull helps overcome contamination, in both vertical and horizontal cases, by placing new cement in with a concept of stages or layers. These layers result from the number of pump and pulled stands required to achieve the overall plug length. This new or uncontaminated cement volume from each stand places it inside the initial volume of cement previously pumped in place, likely exposed to contamination. Figure 4 illustrates the staging or layers concept of the cement placement during the pump and pull.

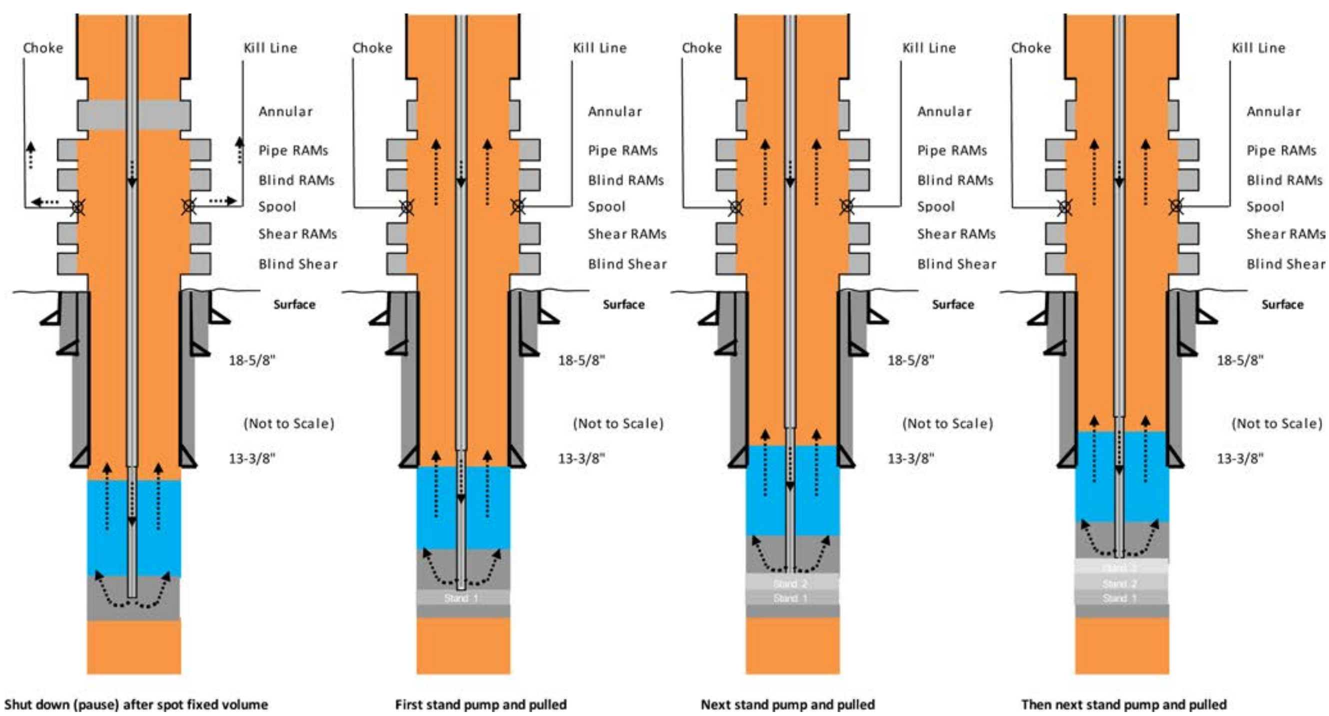

Figure 4—General illustration of the pump and pull cement staging or layers concept

Referencing Figure 1 and Figure 2, if these wellbore abandonment programs could reduce the number of plugs required to achieve the objectives, it would improve the associated operational time resulting in better efficiency.

In Figure 1, plug 2 isolates a hydrocarbon zone and plug 3 isolates the borehole from the cased wellbore; both would require plug integrity testing to confirm achievement of the abandonment objectives. Using the pump and pull method, plug 2 and plug 3 could be set in a single continuous plug of required length. This would eliminate the additional plug integrity testing for plug 2. Similarly, for plug 5 and plug 6, these could be set in a single continuous plug as well.

Figure 5 represents the same wellbore abandonment program in Figure 1 using the pump and pull method to achieve the abandonment objectives. It could eliminate two plugs for the general vertical case that required plug integrity testing.

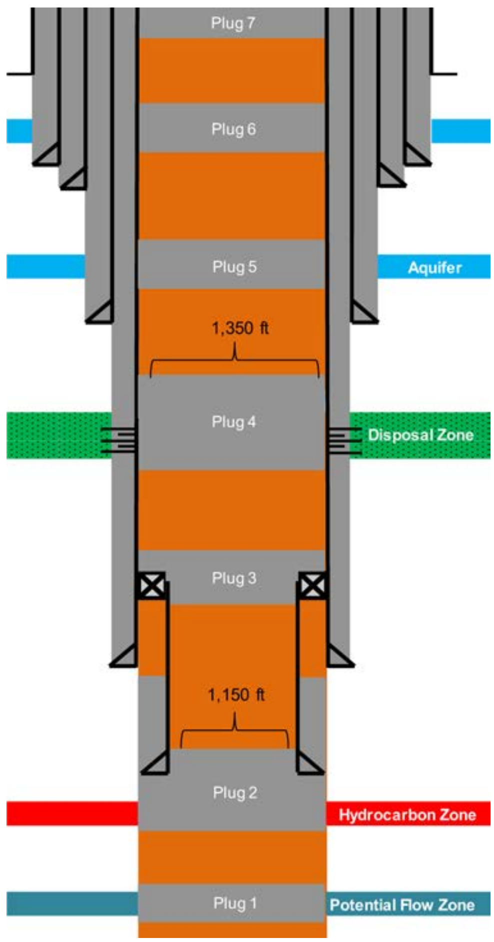

Figure 5—General well abandonment using pump and pull technique (vertical case)

In Figure 2, there are six plugs planned in the open hole section to achieve the abandonment requirements of a hydrocarbon zone in the horizontal section of the well. Using the pump and pull method, the six plugs could be reduced to three plugs by setting each plug set as a single continuous plug. The plug integrity testing required for plug 5 and plug 6 would be reduced yielding improved operational efficiency. Similarly, plug 8 and plug 9 could be set a single continuous plug eliminating the operational time to perform an additional plug integrity test.

Figure 6 represents the same wellbore abandonment program in Figure 2 using the pump and pull method. It could eliminate four plugs for the general horizontal case of which two required plug integrity testing.

The operational time noted captures the plug integrity testing as well as the plug setting time. Whether or not a plug requires integrity testing, the plug setting time includes mixing and pumping in place, pulling through the plug, circulating out any excess clean, and then any wait-on-cement time before setting the second plug. Depending on the rig type, location and environment would help capture the efficiency magnitude.

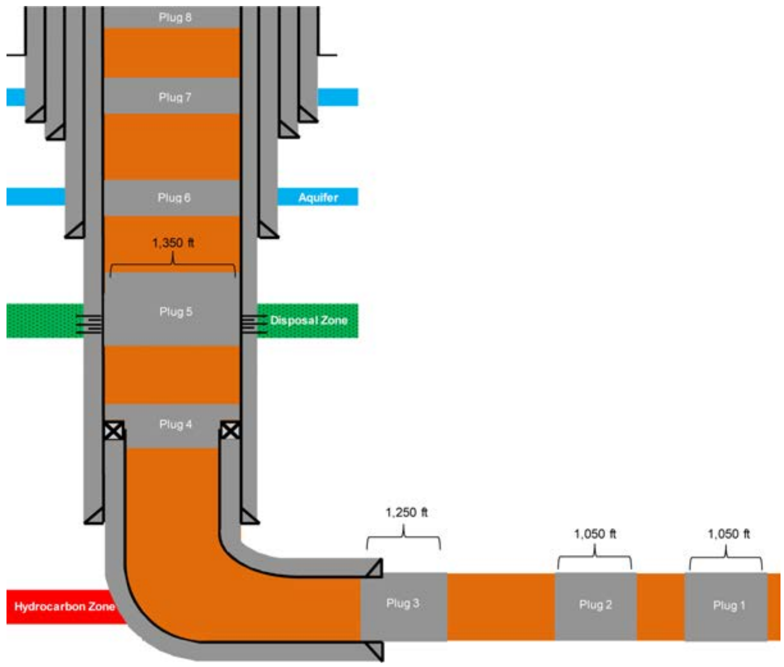

Figure 6—General well abandonment using pump and pull technique (horizontal case)

Risk Management

Due to the operational differences of the deployment scope using drilling rigs without coiled tubing assistance, there should be consideration for the following:

- cement design and laboratory testing
- cement volume required versus workstring capacity
- workstring size versus annular configuration
- pump versus pull rate during placement
- initial volume placed in annulus compared to the total plug volume

The cement design and laboratory testing is important for the job success. Proper cement assurance-testing, accounting for the pump and pull operations, help ensure achievement of the job objectives. The cement design should have a thickening time with sufficient margin for rig specific tasks including connection breaking, racking, and make-up time. This does not include the placement time dependent on the initial volume pumped, the pump and pull rates, and circulating out any excess after placement. Appendix C provides a general laboratory-testing schedule for reference.

There are job design limitations using the pump and pull method. The most notable is the workstring capacity available for the cement volume required. This is common at shallow depths or in the top hole sections of the wellbore. The workstring should allow for the cement volume left inside, prior to starting the pump and pull, to be at least 10 barrels below the rig floor. This enables sufficient spacer volume behind to displace the cement before breaking connections and starting displacement with the rig.

The workstring size selected for placing the initial volume of cement and exposed during the static periods can affect the fluid displacement efficiencies or cement contamination. A ratio of 2.25 annular inside diameter to workstring outside diameter has shown the greatest success rate using the pump and pull method. The preferred workstring size should be available by the time abandonment operations begin. Alternatively, using the closest available size is the less preferred option.

The ideal pull rate during the pump and pull, for determining the surface pump rate, is 15 feet per minute. The 15 feet per minute would be the equivalent annular velocity of the fluid between the outside diameter of the workstring submerged in the cement and the annular inside diameter. To simplify operations, vary the surface pump rate in half of a barrel per minute increments until achievement of the target annular velocity. When abandonment operations take place in slim holes, the surface pump rate can be half of a barrel per minute or less to achieve the preferred annular velocity. For these cases, confirm the minimum rate achievable with the rig pumps. If the rate is greater, adjust the pull rate to the lowest rate equivalent annular velocity.

The initial volume of cement placed outside the workstring dictates the remaining volume left inside the workstring to be pump and pulled. This volume can change depending on the plug objectives and operating conditions. For cased or open hole plugs, the minimum acceptable volume initially placed outside the workstring should result in an annular height less than 500 feet. Ideally, the volume should aim for a couple hundred feet; however, in some annular configurations this minimum volume is not acceptable. An important variable to consider is the applied percent of cement excess for placing open hole plugs with the pump and pull method. The amount of excess can affect the annular cement height especially when there is limited information regarding the actual annular profile. As a result, keep the initial cement volume annular height less than 500 feet using a gauge hole. If the volume with the excess surpasses 500 feet, reduce the initial volume accordingly.

Operations

The pump and pull practice has been deployed in numerous wells, all with good success over a three year period. The following situations help to demonstrate the advantages it may have for different applications.

During construction of an onshore single-lateral injector well, the plan was using cement plugs to isolate a 1,540-foot 8-½ inch horizontal pilot hole, set a whipstock, and the drill the lateral. As the pilot hole was in a hydrocarbon-bearing zone, this required installation of a plug set to achieve the abandonment objectives. With the plugs having to isolate a hydrocarbon-bearing zone, each plug set would require integrity testing. Considering the pump and pull technique, the decision was made to abandon the entire pilot hole with a single continuous plug. The job design for a 1,690-foot cement plug resulted in the parameters seen below in Table 2.

Table 2—Pump and pull design for single-lateral injector well plug-back

Parameter	Value
Workstring-stinger size (W_{sod})	2-⅞ inch (used, 3-½ calculated)
Total cement plug volume (P_{vtot})	135 barrels
Initial volume of cement outside the workstring (P_{iv})	30 barrels
Time to pull one stand (T_{pnp})	6 minutes
Pump and pull displacement rate (Q_{pnp})	1 barrel per minute
Total number of stands to be pump and pulled (S_{tpnp})	16 stands
Cement density	16.4-ppg
Thickening time for the cement plug	7:30
Bottom hole static temperature	222 deg F
Bottom hole circulating temperature	182 deg F

The job was successful as the plug was within 100 feet of the theoretical top of cement. This top of cement was sufficient to run the whipstock to fulfill the plug back requirements. Figure 7 shows the thickening time chart for the cement used in Table 2.

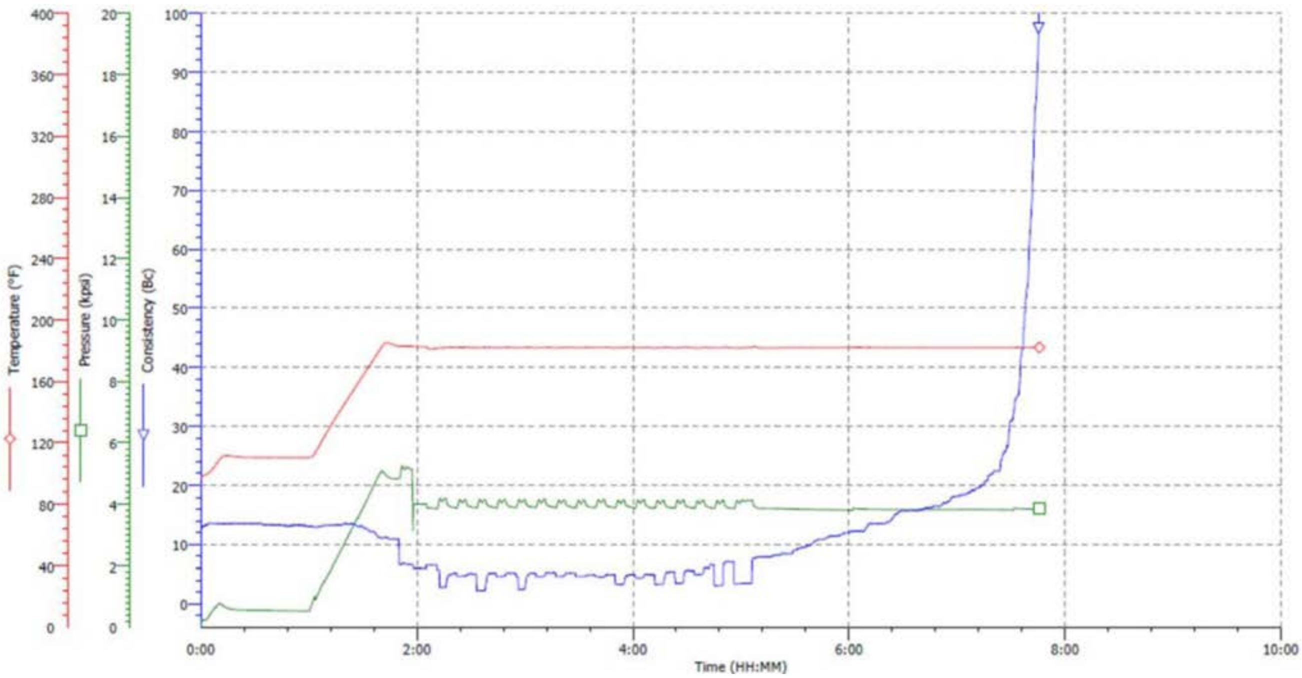

Figure 7—Pump and pull thickening time test for the single-lateral injector well plug-back

A shallow onshore vertical oil well contained potential flow zones and aquifers before achieving the appropriate depths for the zones of interest. During the temporary abandonment, these zones required non-invasive lateral isolation to achieve the abandonment objectives. This resulted in 1,750 feet of isolation. Conventionally the abandonment planned to use four plugs. The planning with the pump and pull consolidated three plugs with a single continuous 1,950-foot plug. The job design resulted in the parameters seen below in Table 3.

Table 3—Pump and pull design for shallow vertical oil well plug-back

Parameter	Value
Workstring-stinger size (W_{sod})	3-½ inch
Total cement plug volume (P_{vtot})	136 barrels
Initial volume of cement outside the workstring (P_{iv})	30 barrels
Time to pull one stand (T_{pnp})	6 minutes
Pump and pull displacement rate (Q_{pnp})	1 barrel per minute
Total number of stands to be pump and pulled (S_{tpnp})	15 stands
Cement density	12.0-ppg
Thickening time for the cement plug	6:45
Bottom hole static temperature	170 deg F
Bottom hole circulating temperature	122 deg F

The plug was successful with no problems during execution and provided the base to set an additional abandonment plug of 600 feet conventionally. The agreement of the second plug from operations was to manage the placement risk of setting a plug of this length for the first time. Figure 8 shows the thickening time chart for the cement used in Table 3. As the design was an extended cement, the set profile was characteristic for pump and pull operations. These designs may experience longer thickening times when under shear in the consistometer. To overcome this, the motor becomes static to simulate actual well conditions of the cement after placement. This enables the cement to build gel strength. The motor becomes dynamic after a given time, ranging from 45 minutes to one hour, hoping to capture a set signature indicating the cement cannot return to a dynamic state. When this occurs, it represents the thickening time.

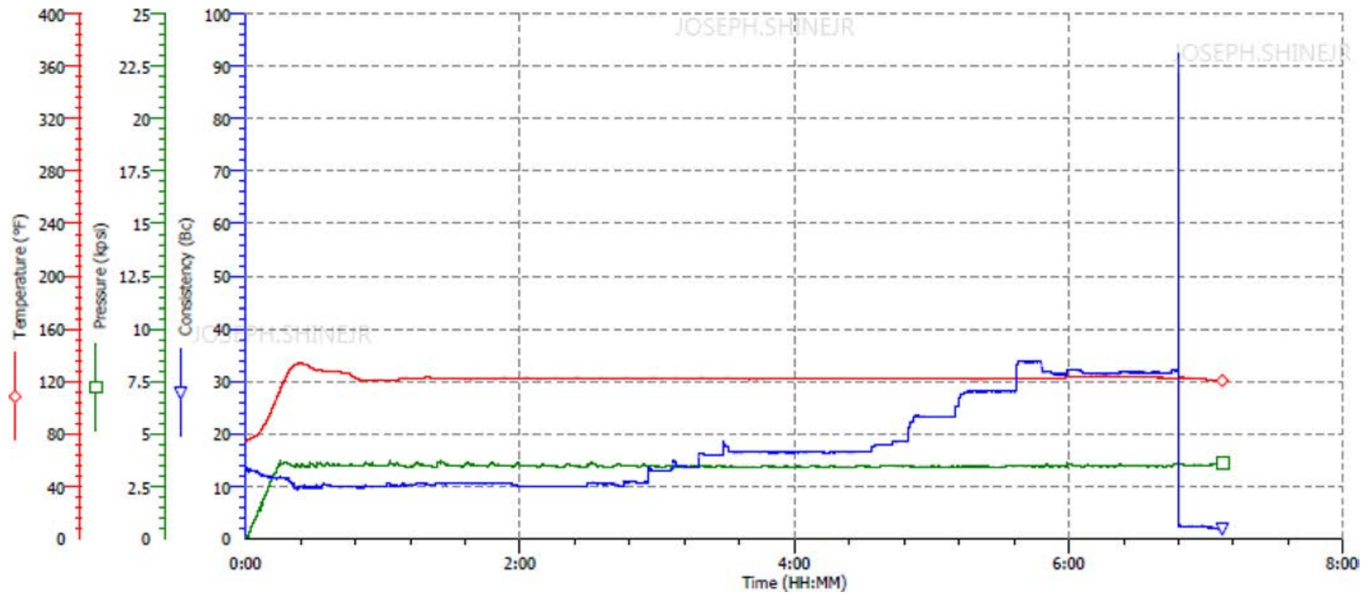

Figure 8—Pump and pull thickening time test for the shallow vertical oil well plug-back

An offshore multi-lateral well planned to use cement plugs to isolate the 1,990-foot 8-½ inch highly deviated pilot hole and then set a kick-off plug to continue the well construction. As the pilot hole was in a hydrocarbon-bearing zone too, this required installation of plug sets to achieve the abandonment objectives. Considering the pump and pull technique, the decision was made to combine the kick-off plug with the pilot hole abandonment in two continuous plugs. The first plug was 1,000 feet to cover half of the pilot hole at a conventional density. The second plug combined the remaining pilot hole with the kick-off plug, a heavier 1,250-foot plug, eliminating the total number of plugs required and the integrity testing prior to setting the kick-off plug. The job design for both plugs is below in Table 4 and Table 5.

Table 4—Pump and pull design for first plug in the multi-lateral well plug-back

Parameter	Value
Workstring-stinger size (W_{sod})	3-½ inch
Total cement plug volume (P_{vtot})	98 barrels
Initial volume of cement outside the workstring (P_{iv})	15 barrels
Time to pull one stand (T_{pnp})	6 minutes
Pump and pull displacement rate (Q_{pnp})	1 barrel per minute
Total number of stands to be pump and pulled (S_{tpnp})	10 stands
Cement density	15.8-ppg
Thickening time for the cement plug	6:45
Bottom hole static temperature	199 deg F
Bottom hole circulating temperature	148 deg F

Table 5—Pump and pull design for second plug in the multi-lateral well plug-back

Parameter	Value
Workstring-stinger size (W_{sod})	3-½ inch
Total cement plug volume (P_{vtot})	113 barrels
Initial volume of cement outside the workstring (P_{iv})	15 barrels
Time to pull one stand (T_{pnp})	6 minutes
Pump and pull displacement rate (Q_{pnp})	1 barrel per minute
Total number of stands to be pump and pulled (S_{tpnp})	14 stands
Cement density	16.4-ppg
Thickening time for the cement plug	6:15
Bottom hole static temperature	195 deg F
Bottom hole circulating temperature	143 deg F

Both plugs were effective. The first plug was within 150 feet of theoretical top of cement proving the base for the second plug. The second plug was within 50 feet of the planned top of cement that enabled sidetracking for drilling the next lateral. See Figure 9 and Figure 10 for the thickening time charts.

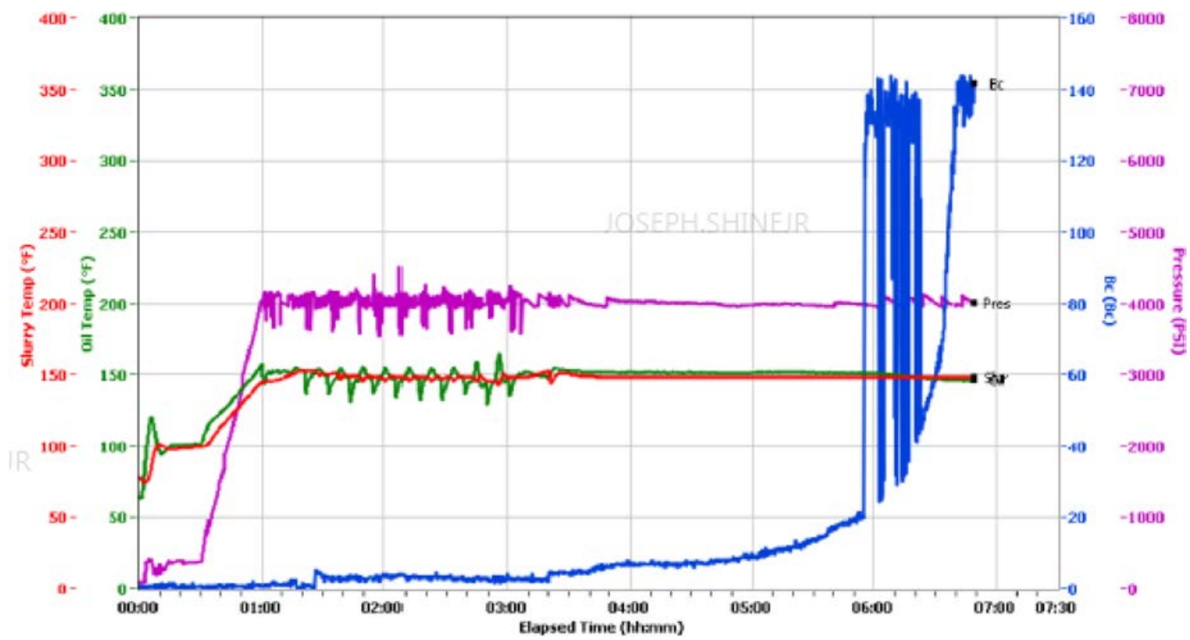

Figure 9—Pump and pull thickening time test for first plug in the multi-lateral well plug-back

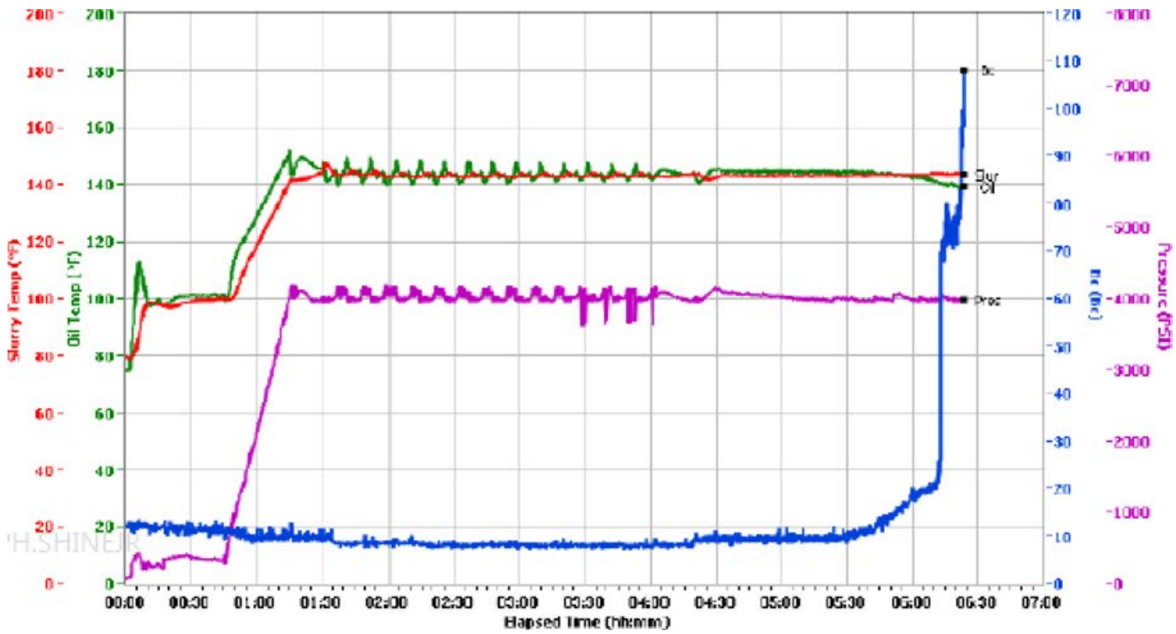

Figure 10—Pump and pull thickening time test for second plug in the multi-lateral well plug-back

A multi-lateral well experienced an unexpected water zone that required isolation in the motherbore. Service providers declined to run mechanical isolation kits due to the deep deployment and H2S exposure risk. The pump and pull method was to set a 625-foot horizontal cement plug at 20,000 feet measured depth and 11,100 feet true vertical depth in a 6-⅛ borehole. The job design for the plugs is below in Table 6.

Table 6—Pump and pull design for isolation plug at 20,000-feet

Parameter	Value
Workstring-stinger size (W_{sod})	2-⅞ inch
Total cement plug volume (P_{vtot})	23 barrels
Initial volume of cement outside the workstring (P_{iv})	8 barrels
Time to pull one stand (T_{pnp})	6 minutes
Pump and pull displacement rate (Q_{pnp})	½ barrel per minute
Total number of stands to be pump and pulled (S_{tpnp})	7 stands
Cement density	16.4-ppg
Thickening time for the cement plug	7:15
Bottom hole static temperature	225 deg F
Bottom hole circulating temperature	185 deg F

The isolation plug was successful as the top of cement tagged up 300 feet higher providing the isolation required continuing the well construction. See Figure 11 for the thickening time chart.

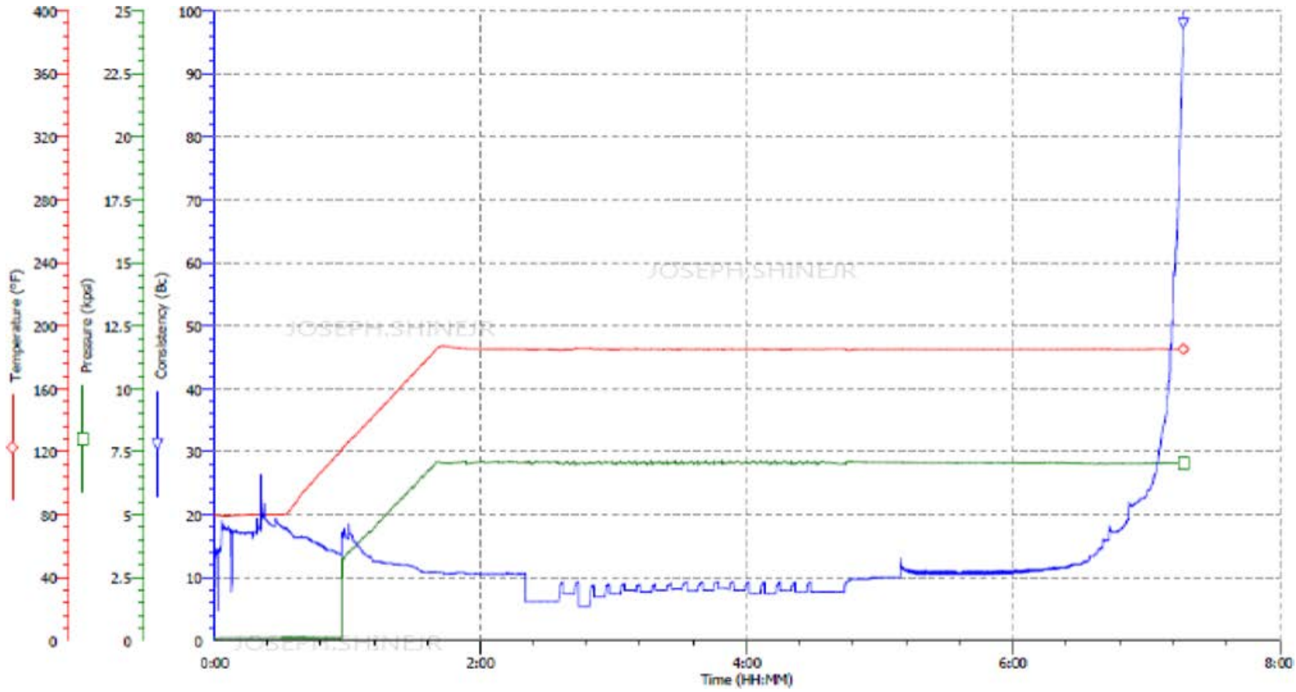

Figure 11—Pump and pull thickening time test for isolation plug at 20,000 feet

Summary

For cement plug installation, during wellbore abandonment operations, the pump and pull method can improve efficiency by reducing the quantity of cement plugs deployed as well as obtain better placement success. The technique allows for the placement of cement plugs with greater lengths than conventional displacement methods. The scope of the method is not limited to the operational summaries discussed above following the risk management guidance, practices presented in the manuscript, and using good engineering judgement. With any plug placement, following the best industry practices still apply for to further support the placement success.

Acknowledgements

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References

Ahrenst, A. et al 2016. Improved Cement Plug Placement Method Resulting in Reduced Rig Time. IADC/SPE Drilling Conference and Exhibition. Forth Worth, Texas. 1-3 March. SPE Paper 178853. 10.2118/178853-MS

Godoy et al 2012. Successful Cementing Through Bottomhole Drilling Assemblies. Abu Dhabi International Exhibition & Conference. Abu Dhabi, UAE. 11-14 November. SPE Paper 161086. 10.2118/161086-MS

Harrison T.W. and Blount C.G. 1986. Coiled Tubing Cement Squeeze Technique at Prudhow Bay, Alaska. *SPE 56th California Regional Meeting. Oakland*, CA. 2-4, April. SPE Paper 15104. 10.2118/15104-MS

Heinold, T. and Shine, J. 2017. Losses? No Problem. Unconventional Solutions to Cure Unconventional Losses and Improve Wellbore Instability Problems in Saudi Arabia. SPE Annual Technical Conference and Exhibition. San Antonio, TX. 9-11, October. SPE Paper 187440. 10.2118/187440-MS

Sankar, R. et al 2003. Challenging the Limits: Setting Long Cement Plugs. SPE Latin America and Caribbean Petroleum Engineering Conference. Port of Spain, Trinidad, 27-30 April. SPE Paper 81182. 10.2118/81182-MS

Shine, J.M. 2014. Planning for a Necessary Evil in Deepwater Operations: Remedial Cementing. SPE Deepwater Drilling & Completions Conference. Galveston, Texas. 10-11 September. SPE Paper 170322. 10.2118/170322-MS

Appendix A

The following describes an approach to design a pump and pull placement for setting a cement plug using a drilling rig. This general series of calculations have enabled the success described in the manuscript.

The procedure begins with determination of the total cement volume required to achieve the plug objective. Being a straightforward calculation, this value is P_{vtot}, expressed in barrels. Knowing P_{vtot}, the workstring-stinger selection for the annular size focuses on the ratio of 2.25. Calculate the value as shown rounding up to the closest workstring-stinger size. For larger annular sizes, the workstring size is usually the workstring-stinger size.

$$W_{sod} = \frac{Ann_{eq}}{2.25} \qquad \text{A.1}$$

Where:

W_{sod} =size of the workstring-stinger outside diameter, inches

Ann_{eq} =equivalent annular size, inches

Knowing W_{sod}, the annular capacity between Ann_{eq} and W_{sod} determines the maximum value for the initial volume of cement outside the workstring-stinger (P_{ivmax}). As discussed, P_{ivmax} should be less than 500 feet using the gauge hole size unless caliper log data is available confirming the accuracy; here use the caliper volume with no excess.

$$P_{ivmax} = \left[\frac{(Ann_{eq})^2 - (W_{sod})^2}{1029.45}\right] * \quad (500 \quad ft) \qquad \text{A.2}$$

Where:

P_{ivmax} = maximum initial volume of cement outside the workstring-stinger, barrels

The difference between P_{vtot} and P_{ivmax} is the pump and pull volume remaining in the workstring, P_{rvws}, expressed in barrels.

$$P_{rvws} = \quad P_{vtot} - P_{ivmax} \qquad \text{A.3}$$

Where:

P_{rvws} = remaining volume of the plug inside the workstring, barrels

This volume, P_{rvws}, has to be 10 barrels less than the remaining workstring volume (W_{sv}) from surface to the ending depth of the workstring denoted as P_{rvten}.

$$P_{rvten} = \quad W_{sv} - 10 \quad bbl \qquad \text{A.4}$$

Where:

P_{rvten} = remaining workstring volume available for the plug less 10 barrels, barrels

W_{sv} = total workstring volume of all sizes used, barrels

If this volume, P_{rvten}, is less than P_{rvws}, do not use the pump and pull or adjust the job design to satisfy this condition. If P_{rvten}, is more than P_{rvws}, proceed forward with planning. Knowing P_{ivmax}, the initial volume of cement outside the workstring should target a length of 150 to 250 feet using the excess percentage or a length that satisfies the operational requirements ensuring it does not exceed P_{ivmax}. This will set a target for the fixed annular height of the plug above the end of the workstring-stinger.

$$P_{iv} = \left[\frac{(Ann_{eq})^2 - (W_{sod})^2}{1029.45}\right] * \quad \left(1 + \frac{X}{100}\right) * (L_{ait}) \qquad \text{A.5}$$

Where:

P_{iv} = initial volume of cement outside the workstring-stinger, barrels

L_{ait} = annular length of initial cement volume outside workstring-stinger, feet

X = excess for cement volume, percentage

Using P_{iv}, determine $P_{rvws'}$ as the difference between P_{vtot} and P_{iv}. $P_{rvws'}$ denotes the remaining volume of the plug inside workstring after performing the previous verification calculations (*A.1* through *A.4*) to determine the plug placement is a pump and pull candidate.

The next calculation is the surface pump rate, Q_{pnp}. These calculations are a function of the annular capacity, used to determine P_{iv}, between Ann_{eq} and W_{sod}, including excess.

$$C_{ann} = \left[\frac{(Ann_{eq})^2 - (W_{sod})^2}{1029.45}\right] * \left(1 + \frac{X}{100}\right) \quad \text{A.6}$$

Where:

C_{ann} = annular capacity of the equivalent annular size and workstring-stinger, barrels per foot Using the target pull rate of 15 feet per minute and C_{ann}, determine the surface pump rate.

$$Q_{pnp} = C_{ann} * 15 \ feet \ per \ minute \quad \text{A.7}$$

Where:

Q_{pnp} = pump and pull displacement rate, barrels per minute

If the pull rate of 15 feet per minute does not meet the job requirements, use a selected pull rate or annular velocity in its place for these calculations.

The last calculation is to determine how many stands or three joints of drill pipe need pulling to complete the placement. These calculations use a 90-foot stand.

$$T_{pnp} = \left(\frac{90 \ ft \ stand}{15 \ ft \ per \ minute}\right) \quad \text{A.8}$$

Where:

T_{pnp} = time to pull one stand, minutes

Use this time to determine how many barrels exit the workstring while pulling one stand.

$$P_{vpnp} = T_{pnp} * Q_{pnp} \quad \text{A.9}$$

Where:

P_{vpnp} = volume of cement displaced during pulling of one stand, barrels

Use this volume, P_{vpnp}, and $P_{rvws'}$ to identify the number of stands to pump and pull.

$$S_{pnp} = \left(\frac{P_{rvws'}}{P_{vpnp}}\right) \quad \text{A.10}$$

Where:

S_{pnp} = number of stands to be pulled rounded down, stands

Using a safety factor of two stands less has demonstrated good results aligning the trailing edge of the cement inside the workstring to the annular height behind the workstring-stinger. This quantity determines the total number of pump and pulled stands used to set the plug in place.

$$S_{tpnp} = S_{pnp} - 2 \quad \text{A.11}$$

Where:

S_{tpnp} = total number of stands to be pump and pulled, stands

Upon completion of the pump and pull operation, it is recommended to pull the workstring out of the remaining plug volume until the end of the workstring-stinger is no less than 500 feet above the top of the theoretical plug.

Appendix B

The following describes an approach to design a pump and pull placement for setting a cement plug using a drilling rig. This general procedure has enabled the success described in the manuscript.

1. Run into the hole with the workstring assembly to the preferred setting depth with ____ feet of ___ inch stinger. (W_{sod})
2. Open the choke and/or kill lines then close the backside.
3. Apply a backpressure of ____ pounds per square inch (if required).
4. Pump ___ barrels of spacer ahead at ___ barrels per minute.
5. Pump ___ barrels of cement ahead at ___ barrels per minute. (P_{vtot})
6. Pump ___ barrels of spacer behind at ___ barrels per minute.
7. Displace with cement unit until ___ barrels of cement exits the workstring-stinger. (P_{iv})
8. Shut down pumping, release pressure, open the backside, close the choke, and/or kill lines.
9. Disconnect the cementing stand, and rack the stand back in the derrick. Make up the top drive.
10. Using the rig pump, displace at ___ barrels per minute (Q_{pnp}) while pulling at ___ feet per minute for one stand.
11. Shut down, disconnect the stand, rack back, make up the top drive and repeat ___ more times until a total of ___ stands are pump and pulled. (S_{tpnp}).
12. Shut down and then pull out of the well until the end of the workstring has cleared the theoretical top of cement by no less than 500 feet.
13. Circulate the wellbore clean and close in the well.
14. Wait on the cement until achievement of the required compressive strength.

Appendix C

The following describes an approach to test the cement plug design for a pump and pull placement using a pressurized consistometer to achieve a thickening time. This general testing schedule has enabled the success described in the manuscript. All other cement testing for performance properties should align with API guidance.

1. Use a batch mix or surface retention time of ___ minutes (if applicable).
2. Ramp to the simulated placement temperature and pressure in ___ minutes.
   (Appendix B, Step 7)
3. Shut down for ___ minutes.
   (Check the estimated rig time to perform Appendix B Step 8 and 9)
4. Turn the motor on for ___ minutes (T_{pnp}) and then motor off for ___ minutes.
   (Check the estimated rig time to perform Appendix B Step 9)
5. Repeat the motor on/off cycle for a total of ___ times. (S_{tpnp})
6. Keep motor off for an additional ___ minutes.
   (Check the estimated rig time to perform Appendix B Step 12)
7. Turn the motor on for ___ minutes.
   (Check the estimated rig time to perform Appendix B Step 13)
8. Keep motor on until an additional ___ minutes of safety margin to complete the thickening time.