

Novel Cement Composition Eliminates Water Flows on Intermediate Strings in Midland and Delaware Basins

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Abstract

Operators drilling in the Midland and Delaware Basins experience annular fluid flow, primarily in the form of water, after cementing the intermediate string at depths of 3000' to 6000'. This can manifest during and immediately after primary cementing or take several weeks or months to manifest. Operators in the field estimate fluid flow occurs on about half of the intermediate casing strings. This paper presents results of a Fluid Flow Control (FFC) cement slurry, specifically designed to prevent water flows during primary cementing and shutoff water flows through remedial squeeze applications. This slurry system is specially formulated at a density range from 13.5 ppg to 14.8 ppg as both a lead or tail cement or stand-alone squeeze slurry across the flow intervals. This FFC cement slurry exhibits low fluid loss, delayed gel strength, zero free fluid, zero slurry segregation, post set expansion and rapid strength development. The additive package in this cement composition provides properties that produce an excellent seal for zonal isolation and shut off of fluid flow.

A total of 75 applications of this FFC cement slurry is summarized in two basic applications: primary cementing and remedial cementing. Flexible density range and multiple functions of the additives reduced design time with lead and tail formulations accomplished by simply adjusting the additive concentration and water requirement. The composition's easy mixability to yield a stable slurry is demonstrated via performance tests. Water flow prevention during primary work as well as mitigation through squeeze applications is documented via field case histories.

The application analysis and case histories illustrate the benefits of FFC cement slurry to reduce rig time and cost of these early-stage well construction operations. Application of FFC cement slurry on 42 intermediate cement jobs reduced fluid flow from 50% to only 9%. For the 33 wells squeezed with FFC cement slurry to mitigate fluid flow, well integrity was restored for 29 with the first squeeze application. Overall cost reduction derived from improved FFC cement slurry performance to eliminate fluid flows is documented.

Introduction

Operators drilling wells in the Midland and Delaware Basins often experience fluid flow after cementing intermediate casing strings. A summary of the typical well conditions is shown in

Table 1. A surface casing is normally 18 5/8" or 13 3/8" and set at 300'. Below the surface casing, drilling continues typically with a brine and 17 1/2" or 12 1/4" open hole to 3000' to 6000'. The intermediate casing is normally 13 3/8" or 9 5/8" but in some cases an 11 3/4" casing is set. This intermediate casing is typically cemented from total depth to surface using fresh water spacer followed by low-density lead and tail cement. General cement slurry designs covering flow zones exhibit densities that are routinely lowered using excess water and light weight additives to extend the cement yield and reduce material cost. When concern for fluid flow is present, the cement slurry is altered to provide a moderate amount of fluid loss control. Despite these changes, fluid flow, primarily in the form of water, is often observed at surface through the intermediate casing annulus. Flow can be detected anywhere from days to weeks or even months after cementing. This flow, which is estimated to occur in between 40% to 60% of wells drilled in select areas of these two basins, originates from several water/gas-bearing zones in that intermediate section.

Table 1 – Summary of Well Conditions in Midland / Delaware Basin

Item	Typical Condition
Total Vertical / Measured Depth	3000' to 6000'
Casing Size	13 3/8" or 9 5/8"
Hole Size	17 1/2" or 12 1/4"
Top of Cement	Surface
Previous Casing Depth	+ or – 300'
Previous Casing Size	18 5/8" or 13 3/8"
Mud Density and Type	9 ppg to 10 ppg Brine
Spacer Type	Fresh Water
Cement Density	13.5 ppg to 14.8 ppg
Normal Cement Design	Low Density Class C Cement Fluid Loss Control Additives

These fluid flows behind intermediate casing usually require remediation before well construction or operation can continue. Repair of this fluid flow requires squeezing of the annulus behind casing. It is estimated that sealing off one of these fluid flows usually require two or three squeeze treatments and several days of non-productive time. This high water-flow frequency and cost of remediation motivated investigation of methods to prevent this annular seal failure during cementing as well as to restore a failed barrier.

Causes of Flow after Cementing

Fluid flow following cementing occurs regularly costing the petroleum industry significant time and resources to mitigate. Flow reaching the surface creates real HSE issues. Fluid migration can occur during well construction or later in the producing life of the well. Fluid flow effects on well operation range from catastrophic to nuisance including blowouts, extended remedial operations, or required pressure monitoring.

A summary of fluid flow after cementing by Watters and Beirut (1998) provides a thorough digest of fluid flow causes and cures. Three different causes for fluid flow are discussed:

- Flow hours or days after cementing caused by pressure decline in the setting cement column
- Long-term leakage months or years after cementing cause by incomplete drilling fluid displacement or cement shrinkage
- Bond degradation due to well bore stresses

The mechanism driving fluid flow after cementing involves pressure transmission and volume loss. Initial hydrostatic pressure in a cemented annulus is designed to be sufficiently high to prevent formation fluid from entering the well. As the cement hydrates, the fluid begins to gel to a point at which hydrostatic pressure of the column is supported. At this point, termed the onset of Transition Time, the cement is still sufficiently fluid to allow permeation of fluid through the column. The Transition Time ends once the hydration reaction has progressed to the point at which fluid can no longer permeate the setting cement. During Transition Time, any loss of cement column volume such as through fluid loss causes a decrease in trapped hydrostatic pressure. If pressure in the column drops below pore pressure of the formation fluid, the fluid can enter the annulus and migrate through the cement.

Pathway for long-term fluid leakage can develop over time via several scenarios:

- Establishing flow channel through drilling fluid bypassed during cement placement
- Chemical shrinkage of the cement during long-term hydration
- Bond degradation due to thermal, mechanical, or hydraulic stresses.

Each of these causes of fluid flow after cementing or long-term fluid leakage can be mitigated to prevent flow in the first place. Many operational and cement modifications could possibly reduce this fluid flow. However, best solution to the problem involved development of a universal cement formula to counteract the occurrence of flow. Investigation of cement designed to control this specific fluid flow issue looked for a comprehensive, cost-effective solution which resulted in development of FFC cement slurry.

Basis of Design

General design criteria were established for the FFC cement slurry development. First, the low-density lead and tail scenario were maintained. This parameter preserved the economic

benefit of extending cement yield while still achieving required set time and strength development targets. A uniquely formulated pair of low-density additives provided slurry stability over a wide density range without adversely affecting slurry mixability or rheology. Additionally, these additives increased rate of strength development.

Considering the specific timing of fluid flow occurring in this investigation (shortly after or up to months after cementing), neither fluid flow mechanism outlined above could be eliminated as a cause. So, the FFC slurry design considered counteracting both water flow after cementing as well as long-term leakage.

Preventing flow immediately after cementing requires fluid loss control to limit cement volume reduction and gel strength modification to shorten Transition Time. Fluid loss control to mitigate flow after cementing must be under 100 cc/30 min as measured according to API RP 10B-2 (2013). Gel strength modification can be affected either of two ways as illustrated in Figure 1. Creating a thixotropic cement slurry shortens Transition Time through rapid gel strength development immediately after pumping stops (see Figure 2). Thixotropy can be accomplished fairly easily at well temperatures for this application. However, thixotropic cements are usually viscous and difficult to mix. Additionally, rapid gelation may hinder resumption of pumping thixotropic cement after temporary shutdown. Delaying gel strength development (see Figure 3) keeps the fluid un-gelled for an extended period after placement followed by a short Transition Time prior to setting. This behavior, which is more difficult to produce but easier to apply, was selected as the target for this development.

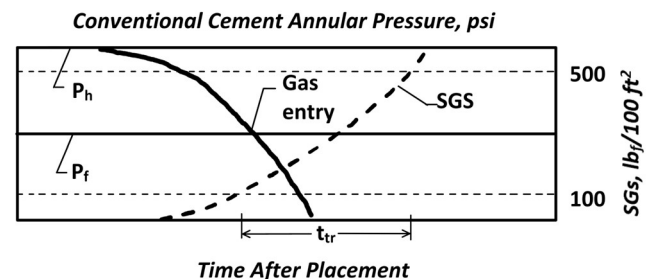


Figure 1 – Normal Cement Behavior (after Watters and Beirut, 1998)

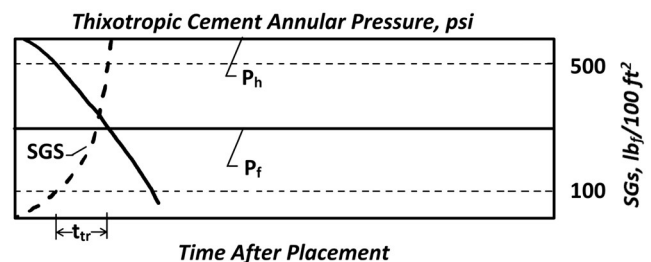


Figure 2 – Thixotropic Cement Behavior (after Watters and Beirut, 1998)

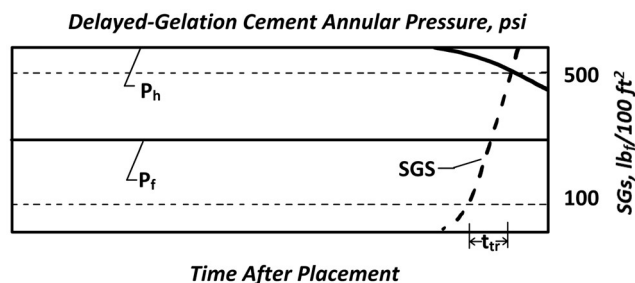


Figure 3 – Delayed Gel Strength Cement Behavior (after Watters and Beirut, 1998)

Preventing long-term flow requires cement expansion along with adequate strength. Cement expansion and strength development were added to the design criteria.

FFC Cement Slurry Design

Creating a cement composition to combat the water flow behind intermediate casings cemented in the Midland/Delaware basins was a multi-step process addressing each desired attribute individually. The process leading to FCCS formulation included confirmation steps to ensure that additives intended to produce one required attribute did not adversely affect or eliminate other required performance.

The final FCCS cement additive package consisted of two slurry stability additives, two fluid loss additives, and an expansion additive.

Free Fluid / Slurry Stability

After testing multiple light weight additives, a pairing of two low density materials for the FFC slurry demonstrated adequate control of free water and rheology. Surprisingly, this control was effective over a wide density range encompassing both lead and tail slurry densities with one dosage level. This range of application allowed mixing lead and tail cements form the same bulk blend by simply adjusting water requirement.

Fluid Loss

As with light weight additives, a pair of fluid loss additives in the FFC slurry produced the most effective control. This combination consisted of a dispersing fluid loss additive and a viscosifying one. The combination delivered required fluid loss control with lower concentration than either individual chemical.

Delayed Gel Strength

Fortunately, the unique combination of light weight and fluid loss additives also produced delayed gel strength development in the FFC slurry. This performance property is not fully understood chemically and is therefore difficult to achieve. However, gel strength development testing of the low-density, low-fluid-loss cement composition revealed delayed gel strength development. All four additives were required to produce desired gel strength development. This serendipity highlights the value of pragmatic, empirical testing methods.

Expansion

An expansion additive tailored to perform in the target temperature range produced the required post-set expansion.

Details of the FFC composition's development, performance properties, and successful application in primary and remedial cementing applications for Midland/Delaware Basin intermediate casings are presented. Performance improvement and cost benefits attributed to the new composition are analyzed.

Properties of Fluid Flow Prevention Cement Slurries

As discussed in the Introduction, cement compositions must be formulated with the necessary additives to produce properties that can control fluid migration. Table 1 lists the generic slurry composition that is the focus of the FFC system. Each individual additive is listed with the range of concentration. The specific tests and the test results for the FFC slurry that is highlighted in this paper will be discussed in the following section. Each item will be discussed separately for clarity, but all the properties will work together to produce a cement optimized for controlling fluid flow both in primary cementing and remedial treatments.

Table 2 – Typical Slurry Composition/Additive Concentration

Item	Description	Amount of Additive
Cement	Class C High Sulfate Resistance	100%
FL 1	Viscous Fluid Loss	0.2 to 0.5%
FL 2	Dispersing Fluid Loss	0.2 to 0.5%
EA 1	Expansion Material	1 to 3%
SA 1	Gel / Free Water / Segregation	0.1 to 0.3%
SA 2	Gel / Free Water	3 to 5%
Water	Fresh	9.2 to 6.5 gal/sk
Density	-	13.5 ppg to 14.8 ppg

Table 1 indicates that the FFC composition contains several additives to provide the necessary properties to mitigate fluid flow. The cement used is significant in that it is a Class C cement which is a high sulfate resistance cement that is always used in the Midland and Delaware basins due to the presence of sulfate in the wells. Typically, slurries containing Class C cement will be mixed at lower densities than other oil well cements due to the finer grind of the Class C. Two different fluid loss additive were used in the formulation (designated by FL1 and FL2). FL1 is a viscosifying polymer and FL2 is a dispersing polymer. This combination is by design. Typically, these polymers are used in combination at concentrations of 0.2 to 0.5%. Additionally, there is an expansion additive used in the slurry and is designated EA 1. Typical concentrations are from 1 to 3% by weight of cement. There are two special additives used in the slurry (designated by SA 1 and SA 2). These materials have multiple functions in the slurry. They both produce an enhanced gel structure and help control free water, slurry segregation, and viscosity. They are used in the range of 0.1 to 0.3% and 3 to 5% respectively.

Table 3 below summarizes the lab test results for FFC cement slurry. Six important test results translate into a cement

composition controlling fluid migration. They are listed in the table with the corresponding test result range that is desired from each test. Each test will be examined in detail in the following sections.

Table 3 – Performance Tests for FFC Cement Slurry

Property	Lab Test Result
Fluid Loss Lead	<150 cc API
Fluid Loss Tail/Squeeze	< 100 cc API
Static Gel strength	<30 mins Transition Time
Post Set Expansion	>0.2% Expansion
Free water/Slurry Segregation	0%/< 5%
Rapid Strength Development	>500 psi in 8 hours

Lab Testing of FFC Cement Slurry

Pre-job laboratory confirmation of the FCCS properties to control fluid migration is necessary. The properties that the slurry produces must be in line with expectations to produce properties necessary to control the fluid migration in the well. Six different tests will be examined in detail in the following sections.

Fluid Loss Results

The first test parameter is fluid loss control measured by the standard fluid loss test. This test is a standard API test (API, 2013) that utilizes standard equipment that all cement labs have. This test however is very important as the fluid lost from the cement slurry must be minimized to prevent fluid flow.

Table 4 – Typical Design Fluid Loss for the FFC System

Cement Slurry	BHCT BHSqT / BHST	FL 1 / FL 2 / Dispersant	API Fluid Loss
13.5 ppg	80 °F - / 90 °F	0.25% / 0.25% / -	106 cc/30 min
13.5 ppg	"Squeeze" 113 °F / 130 °F	0.4% / 0.4% / -	86 cc/30 min
14.8 ppg	"Squeeze" 97 °F / 111 °F	0.25% / 0.25% / -	94 cc/30 min
14.8 ppg	"Squeeze" 110 °F / -	0.5% / - / 0.5%	100 cc/30 min

Note: FL 1 is viscosifying and FL 2 is dispersing

Static Gel Strength Testing

The development of static gel strength is an important property of the FFC cement slurry. The standard SGSA (Static Gel Strength Analyzer, a version of the Ultrasonic Cement Analyzer) can be used to test the slurry as to its gelation characteristics. There are several important data that is obtained from the SGSA. The following table summarizes several slurries used in this investigation to develop the static gel strength profile. The first property is the Zero Gel Time. This is the time where the cement slurry shows no static gel strength. This is desired to be at least one hour. The second critical property is the Transition Time. This is the time that the cement slurry transitions from a low static gel strength (< 100 lbs./100 sqft) to a high static gel strength (500 lbs./100 sqft). This is desired to be less than 30 minutes. All the FFC shown in Table 5 meet the criteria described. A typical static gel strength chart is shown in Figure 4.

Table 5 – Typical Gel Strength for FFC System

Cement Slurry	BHCT BHSqT / BHST	Zero Gel Time End of Gel Time	Transition Time
13.5 ppg	80 °F - / 90 °F	1:10 1:25	15 min
13.5 ppg	97 °F - / 110 °F	1:06 1:19	13 min
14.5 ppg	"Squeeze" 97 °F / 111 °F	1:06 1:19	13 min
14.8 ppg	"Squeeze" 110 °F / -	1:42 1:53	11 min

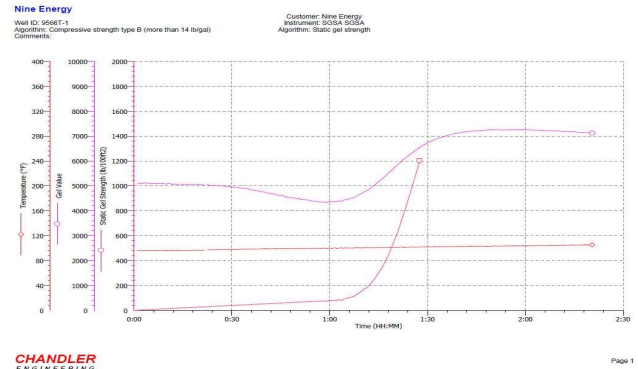


Figure 4 – Static Gel Strength Chart from SGSA

Post Set Expansion

Once a cement slurry has been placed, it is desirable for the set cement to have post set expansion properties. These properties are provided by reactive metals in the cement which produces large crystalline products which produce expansion. Normally this expansion is measured with special linear expansion devices. This mold is filled with the cement slurry in question and then placed in a water bath at the downhole static temperature for one hour. The gap between reference points is measured as an initial baseline reading. Readings are then taken daily for up to 7 days to measure the linear expansion % that is produced in the set cement. Figure 5 shows a typical expansion over a 7-day period that was achieved with one of the FFC compositions. The expansion will vary somewhat due to several items: slurry density, additive concentration, and downhole temperature. Figure 5 shows that most of the expansion in this case occurs in the first 24 hours (0.23%) and then levels off at 48 hours at a value of 0.27%. Figure 6 shows the round expansion mold that is used to measure the linear expansion.

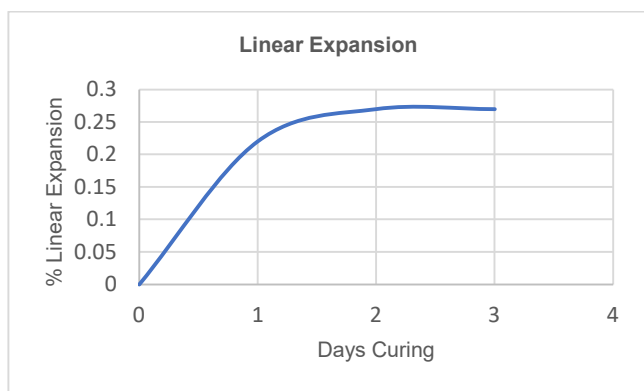


Figure 5 – Measurement of Liner Expansion



Figure 6 – Round Expansion Mold

Free Water / Slurry Segregation Control

A slurry that is designed to control fluid migration must have control of both the free water and the slurry segregation. Free water is a standard API test (API 2013) that is conducted on almost every slurry that is pumped in wells. However, the property required for the FFC slurry the free water must be designed to a value of zero. Below are two tables summarizing the results of two different FFC systems. First Table 6 shows the free water design of slurries both at 13.5 ppg and 14.8 ppg at several different temperatures.

Table 6 – Free Fluid of FFC Cement Slurry

Cement Slurry	BHCT BHSqT / BHST	Free Fluid
13.5 ppg	80 °F - / 90 °F	0.0%
13.5 ppg	97 °F - / 110 °F	0.0%
14.8 ppg	"Squeeze" 110 °F / -	0.0%

Table 7 summarizes segregation test results for two different slurries in the FFC composition family. The slurry is mixed and placed into a fluid loss cell at BHST and allowed to set. The set cement is cut into 8 wafers and the corresponding density is measured using Archimedes principle (this test is commonly referred to as BP settling). The settling test requirement must be less that a total 5% maximum variation from the average.

Table 7 – Typical Segregation/Two Different FFC Systems

Design Density 13.5 lb./gal Section Density	Design Density 14.9 lb./gal Section Density
14.0	na
14.0	15.2
13.9	15.3
13.9	15.2
13.8	15.2
13.8	15.2
13.8	15.2
13.9	15.2
<4% Variation	<3% Variation

Note: Set cement will have a higher density than the mix density due to hydration

One slurry property that helps both the free water control and the slurry segregation is good control of the rheology profile. That means that the slurry when mixed is thin to pump and place but the rheology does not greatly thin with temperature. The FFC cement slurry is unique in that Plastic Viscosity (PV) and Yield Point (YP) at downhole temperature are slightly higher than at surface conditions. This enhances the slurry capability to maintain zero free water control and limited slurry segregation. Table 8 indicates that in the slurry shown the PV/YP at BHCT is always higher than that at surface.

Table 8 – Typical Rheology Profile of FFC Composition

BHCT/BHST F	PV/YP @ Surface	PV/YP @ BHCT
80/113	165/14	262/39
80/90	54/11	59/20
80/97	118/15	134/24

Compressive Strength Development

As stated in the introduction, compressive strength development of the FFC slurry composition is critical to help maintain the seal on the cemented annulus or the squeeze treatment. Short term well interventions can produce stresses in the cement so that the seals can give way if the strength is not high enough. A key property of the FFC compositions is that they develop rapid strength at bottom hole conditions. Table 9 shows examples of the initial set (50 psi strength), 500 psi, 8 hour, and 12-hour compressive strengths. It is designed so that the set cement will develop at least 500 psi in less than 8 hours. The 12-hour compressive strength requirements are at least 800 psi. The examples shown all meet the criteria. Figure 7 shows a typical UCA compressive strength chart.

Table 9 – Typical Compressive Strengths of the FFC System

Density	BHST	Compressive Strength IS/500 psi	Compressive Strength 8 hour/12 hour
13.5	90 °F	3:30/7:18	591/940
13.5	111 °F	3:23/5:48	931/1404
14.8	110 °F	3:09/4:51	1056/1431

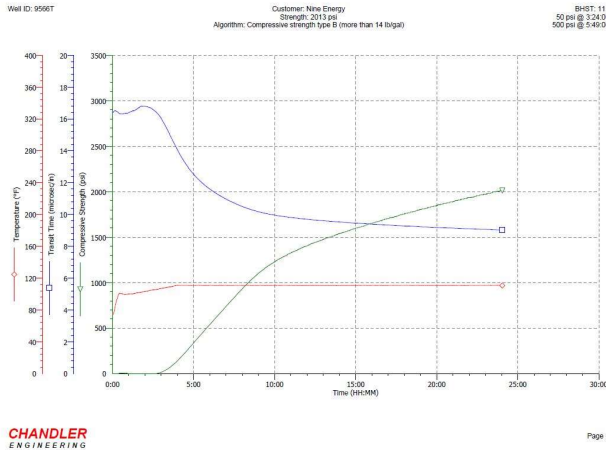


Figure 7 – Typical Ultrasonic Compressive Strength Chart

Operational Considerations

When cementing wells to shut off the fluid flow the cement slurry is a critical factor. However, there are some key operational considerations that must also be considered to maximize success. These are listed below. The factors are broken down in primary cementing and squeeze cementing.

Table 10 – Operational Considerations with Primary and Squeeze Cementing

Factor	Primary	Squeeze
Condition the hole prior to cementing	Yes	If possible
Utilize appropriate Spacer/Flush	Yes	Yes (Reactive Flush Train may be used)
Centralize the pipe	Yes	NA
Pump at maximum allowable velocity	Yes	NA
Establish injection rates and pressures	NA	Yes
Establish a static well (well fluid density in equals well fluid density out)	Yes	If possible
Pump adequate volume to achieve isolation	Yes	Yes

Case History #1: Fluid Flow Shutoff for Primary Job

A customer set a 11 3/4” casing at 3209 feet. The primary objective was to cement to surface and to control the flow of fluids with a special anti-flow cement slurry. Sustained fluid pressures were observed in this annulus in previous wells in the area of the Midland Basin. A cement slurry was designed both a lead and tail of a 14.8 ppg FFC composition. This section was drilled with a cut brine fluid at 10.1 ppg. A volume of 350 bbls of lead cement was pumped followed by 191 bbls of tail cement both at 14.8 ppg. The properties designed for the two systems were slightly different with the tail cement requirement more control than the lead. The lead had a thickening time of 6 hours 38 minutes while the tail has a thickening time of 3 hours 22 minutes. This was designed so that the tail cement would set prior to the lead to maintain hydrostatic pressure as high as possible with the lead cement on the flow zone of interest. The transition time of the lead was 32 minutes and the tail was 29

minutes at BHCT. The cement was pumped into the well following a fresh water spacer of 50 bbls. Some 369 bbls of fresh water was used to displace the cement into the annulus. After placement the floats held and the cementing pump truck rigged down. There was cement slurry to the top of the annulus and after setting the well did not flow at all. Once the operation was complete casing was cut 12 hours later and no fluid pressure was detected at the surface. The customer was pleased with the results.

Case History #2: Fluid Flow Shutoff in Squeeze Treatment

An operator in the Delaware Basin called about a well in Reeves County in which they had a hole in the casing of an existing well and they were getting water, amongst other fluids, flow from an existing disposal well next door. The job was squeezed with the FFC. The customer had a 13.0# kill mud in the hole. An injection rate was established prior to the cement job at 4 bpm at 2000 psi with this well fluid. It was decided to use a retrievable packer to perform the job. The pre-job injection rate was 3 bpm and 250 psi with fresh water 20 bbls of a reactive flush was pump ahead of the cementing treatment. The job was displaced with fresh water. A volume of 65 bbls of the FFC slurry at 14.8 ppg was pumped into the well and a hesitation technique was used while pressuring the cement system. The well was shut in. The waiting time on the cement was 24 hours. It was drilled out and tested the casing to 1500 psi. The pressure held and the job considered a success.

Summary of FFC Cement Jobs for Primary Cementing Flows

The total primary jobs conducted in the Midland and Delaware Basins using the FFC slurry are shown below:

- Total jobs: 42
- Success rate: 91%
- Temperature range: 80 °F to 115 °F
- Density range: 13.5 ppg to 14.8 ppg

For a single well experiencing fluid flow assuming a standard cost of the rig time at \$40,000 a day and could take on average 3 days to fix, the cost to the operator is around \$120,000. Additionally, the cost of the remediation could be an additional \$25,000 up to \$50,000, depending on whether one or more remediation jobs was required. If it is assumed that two squeeze jobs might be performed to successfully seal the flow, successful cementing of the primary intermediate casing can save the operator some \$170,000. Success rate of 91% translates to only 4 wells cemented with FFC experiencing flow compared to an estimated 21 wells assuming the previous success rate of 50%

Summary of FFC Cement Jobs for Remediation

The total of 33 jobs were conducted in the Midland and Delaware Basins using FFC slurry for remedial fluid shut off is shown below.

- Total jobs: 33
- Success rate: 89%
- Temperature range: 80 °F to 125 °F
- Density range: 14.5 ppg to 14.8 ppg

Previously operators in the area estimated a squeeze success rate of 50% for remediation of fluid flow. Cowen (2007) indicated the average number of times needed to squeeze a problem casing would be about 2 to 3 times. Employing FFC cement slurry resulted in 89% success after one squeeze. Total savings to the operators using FFC slurries to squeeze can be estimated.

For 33 wells with a success rate of 50% and assuming a day rate on rig of \$40,000 and a remediation cost of \$50,000, the total cost associated with normal operations would be \$170,000 for each of 16 leaking wells or a total cost of over \$2,800,000. Having an 89% success rate the cost of the failure would roughly be \$620,000 total for the total numbers of failure.

Conclusion

1. The FFC cement slurry composition has several properties that can help eliminate fluid flow in the Midland/Delaware Basin intermediate strings.
2. Critical cement performance properties are necessary to prevent fluid flow: fluid loss control, gel strength development, post set expansion, free water, segregation, and rapid strength development.
3. Using the FFC system in primary cementing has produced highly successful barriers to flow at a significant cost savings to the operator.
4. Using the FFC system in squeeze cementing to seal off water flow behind intermediate strings has been highly successful and delivered significant cost savings.

Nomenclature

<i>SGSA</i>	= <i>Static Gel Strength Analyzer</i>
<i>UCA</i>	= <i>Ultrasonic Cement Analyzer</i>
<i>ppg</i>	= <i>Pounds per Gallon</i>
<i>bbl.</i>	= <i>Barrel</i>
<i>BHST</i>	= <i>Bottom Hole Static Temperature</i>
<i>BHCT</i>	= <i>Bottom Hole Circulating Temperature</i>
<i>BHSqT</i>	= <i>Bottom Hole Squeeze Temperature</i>
<i>cc</i>	= <i>cubic centimeters</i>
<i>sqft</i>	= <i>square feet</i>
<i>lb</i>	= <i>pounds</i>

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