FILTRATE CONTROL - A KEY IN SUCCESSFUL CEMENTING PRACTICES

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INTRODUCTION

In 1961, Beach, O'Brien and Goins, published the results of a study of squeeze-cementing perforations.[1] The study was made over a four-year time span and involved actual wells located primarily in South Texas. The publication gives a comparison of the squeeze practice of that time of attaining pressures equal to overburden pressure and "putting away" relatively large volumes of cement, to the new concept of low-pressure "hesitation" or the "walking" squeeze. The former method made use of normal slurries and the latter of filtrate-loss-controlled slurries. The squeeze success ratio climbed from about 60% for the normal slurries to 85% for the filtrate-loss-controlled slurries. Perhaps the most spectacular success was a well in Yoakum County, Texas, where 230 feet of perforations were successfully squeezed with 100 sacks of cement in a single stage. This is believed to be the first publication showing filtrate-loss control as a key to successful cementing. This work reversed the industry's thinking on squeeze-cementing technique.

During the interim period to 1967, low filtrate-loss cement was gaining popularity for primary cementing, especially for liner cementing where the annular clearance was small and high differential pressure was anticipated. Research studies during this period developed better additives and some unique placement techniques, such as Long Life Cement.[2] Long Life Cementing is basically a two-step operation: (1) the cement is placed in the bottom of the hole, then (2) the casing is lowered into the cement. The method has been used to successfully cement full casing strings, liners and multiple string completions. Depending on the depth of the well and the capability of the rig, considerable time can elapse from the spotting of the cement until the pipe is in place. During this interval the cement must be prevented from chemically setting and physically dehydrating. Low filtrate-loss cements are a necessity for Long Life Cementing.

Gas communication through cemented intervals was recognized at about this same time, the mid 1960's. The problem was first noted in gas storage wells and later in gas producing wells. Laboratory model studies have been made to determine the source of the problem.[3,4] Of the variables, or factors, studied in the models, cement dehydration was found to be the second most important factor contributing to gas leakage into the wellbore. Cement slurry density took first place. It should be emphasized that all factors contributing to gas migration into the wellbore in some manner produce a hydrostatic pressure in the borehole that is less than the formation pressure. Later work by Carter et. al.,[5] showed displacement techniques also aided in preventing gas leakage. Application of low filtrate-loss cements and pipe movement coupled with turbulent flow cementing rates have helped in overcoming some of the gas leakage problems.

Premature dehydration of the cement slurry due to lack of fluid-loss control may be the primary cause of gas communication; this problem is most evident where permeable zones of varying formation pressures occur. Slurries without adequate filtrate-loss control may dehydrate across the permeable zone when hydrostatic pressure exceeds formation pressure, bridging the annulus with cement filter cake. Below the bridging point in the annulus the hydrostatic pressure is relieved, which may allow gas migration from a higher pressure zone to one of lower pressure, thus cutting gas channels in the cement column.

Standard API Fluid Loss tests have been the basis for prior filtrate-loss control considerations in primary and squeeze cementing. The API test provides a 30-minute fluid-loss value through a 325 mesh screen at various differential pressures. No direct method has been proposed to define a good or adequate level of fluid-loss control.

This paper presents a method for evaluating the fluid-loss requirement necessary to obtain successful liner or casing cementing, based on dehydration rates as they may occur during an actual cementing job.

FILTRATE CONTROL DURING CEMENT PLACEMENT

The fluid-loss characteristics of a cementing slurry should first be considered during the displacement of the slurry into the annulus between the pipe and the borehole. During displacement, if the slurry comes in contact with a permeable zone, it will lose filtrate to the zone and deposit a cement filter cake at that point. As the displacement continues, all the slurry passing this permeable zone will lose filtrate to the zone with a corresponding deposition of filter cake on the wall of the hole. The growth of this filter cake may cause an increase in the required circulation pressure or necessitate a reduction in the rate of displacement. When the filtrate loss is excessive, the filter cake may block the annulus, preventing the further displacement of the slurry.

An increase in circulation pressure caused by the buildup of filter cake may cause formation breakdown, especially when the hydrostatic pressure is already close to formation breakdown pressure. Also, where high circulation pressure requires a decrease in pump rate, the mud displacement efficiency may be reduced and thereby add to gas leakage problems.

The amount of filtrate that can be lost to a formation before the annulus is completely filled with cement filter cake will be dependent on annular size. The smaller the annulus, the less the filtrate loss necessary for dehydration of the cement slurry to the point where the filter cake completely blocks, or bridges, the annulus. The amount of filter cake deposited by the loss of a unit volume of filtrate will be affected by the water/solids ratio of the slurry. The higher the water content of the slurry, the larger the volume of filtrate will be to cause the annulus to be completely filled with filter cake. In laboratory tests with Class H Cement mixed with 38% water for example, it was observed that a hard filter cake was formed when 0.330 cc of filtrate was lost from each cc of slurry. The ratio of filtrate volume to cake volume for this slurry was 0.492. Other typical values for different slurry compositions are shown in Table 1. Calculation of the amount of filtrate that will be lost per unit area of the hole to completely fill the annulus with filter cake is made possible by using the filtrate-volume to cake-volume ratio and the annular dimensions.

TABLE I

Filtrate Volume to Filter Cake Volume Ratio
1000 psi Differential Pressure

Cement Compostion	Water Ratio Percent	Volume Ratio Filtrate/Filter Cake
API Class H	38	0.492
API Class H with 35% Coarse Silica	38	0.475
50-50 Pozzolan Cement	57	0.718
50-50 Pozzolan Cement with 6% Gel and 1% Fluid Loss Additive	76	1.108
API Class H with 8% Gel	86	1.120
API Class H with 35% Silica Flour	54	0.492

In order to determine a filtrate-loss rate, the contact time of the slurry with the formation must also be considered. The time during which filtrate will be lost will depend on the location of the zone in the cementing interval, the annular volume, and the displacement rate. At points near the bottom of an interval, fluid loss will occur from the time the slurry reaches this point until all the slurry has been placed in the annulus. This time and the filtrate volume per unit area for the complete filling of the annulus with filter cake allows the calculation of the maximum filtrate-loss rate at this point in the annulus. If the fluid-loss rate is higher than the calculated maximum filtrate-loss rate at this point, the annulus will be filled with filter cake before the displacement of the cementing slurry is completed.

At points further up the hole, higher values for the maximum filtrate-loss rate are permitted since the contact time will be shorter. The most troublesome points will be those with the highest differential pressure and the longest contact time.

The maximum filtrate-loss rate for complete dehydration during cement placement may be calculated for each zone by the following relationship:

$$\text{Maximum filtrate loss rate} = \frac{\text{Annular Volume per ft of Hole} \times \text{Filtrate Volume/Cake Volume}}{\dfrac{\text{Surface Area per ft of Hole}}{\text{Contact Time}}}$$

This may also be expressed as:

$$\text{Maximum filtrate-loss rate} = \frac{21.488 \times Q \times FCR}{DH\ (ZD - CT)}$$

Q = Cement Displacement Rate, BPM
FCR = Filtrate Volume to Cake Volume Ratio
DH = Hole Diameter, in.
ZD = Zone Depth, ft
CT = Depth of Cement Top, ft

From this equation, the maximum filtrate-loss rate will be calculated as ft^3/ft^2-min. If the actual filtrate-loss rate of the slurry is equal to or greater than this value, total dehydration may occur during the displacement. If the loss rate is lower, total dehydration and bridging of the annulus should not occur during the displacement.

FILTRATE CONTROL AFTER CEMENT PLACEMENT—PRIOR TO CEMENT SET

The next area of importance in slurry design based on fluid-loss considerations is the time after placement while the slurry remains in a fluid state. During this time, the slurry may continue to lose filtrate to permeable formations. It is still the zone where the highest differential pressure is present that will present the greatest problem with respect to dehydration of the slurry and bridging of the annulus.

When a cement slurry with inadequate fluid-loss control is used, total dehydration may occur and allow the annulus to be bridged. The continued loss of filtrate to permeable zones below the bridge will reduce the pressure originally trapped below the bridge. If the pressure is reduced to less than the pressure in any of the zones below the bridge before the cement sets, communication may occur in the annulus.

It can be seen that this situation is very much the same as that which occurs during the placement of the slurry. The main difference between these two periods would be the much longer contact time of the cementing slurry with the permeable formations while the slurry is in a static state prior to set. Since the slurry will continue to lose filtrate over this longer time period, better fluid-loss control is generally required to prevent total dehydration and bridging of the annulus.

Calculation of the maximum filtrate-loss rate under these conditions is similar to those shown for the maximum filtrate-loss rate during placement. In this case, the contact time becomes the total time that the slurry is in contact with the permeable zone prior to set, including the time required to place the slurry.

FILTRATE LOSSES AFTER BRIDGING BY FILTER CAKE OR SET CEMENT

For many years, the setting of cement was visualized as progressing from the bottom to the top of the cement column. The rate of cement hydration into a set mass is a function of temperature and time; the higher the temperature the faster the hydration reaction. It has been customary to think of higher temperatures associated with greater depths. However, some researchers[6,7] have reported higher circulating temperatures occurring some distance above the lower end of the pipe. This temperature anomaly may cause cement up the hole to set first. This part of the cement has also been exposed to well temperatures for the longer time. Loss of filtrate to permeable zones during placement may also lower retarder concentrations as well as decrease the water-cement ratio, both contributing to the early set of cement. With these considerations, it should not be assumed that the set will always occur from the bottom up.

Laboratory tests[8] conducted to evaluate hydrostatic bridging characteristics of cement slurries during initial set periods indicate the cement fails to transmit full hydrostatic pressure even before the initial set. This failure may be attributed to slurry gellation or thixotropic properties prior to initial set. The laboratory studies also showed the cement column would not transmit any hydrostatic pressure after final set.

Should initial set or filter-cake bridging occur at some point in the annulus above a high-pressure fluid or gas zone, only the trapped pressure below the point of cement-set or filter-cake bridge prevents fluid or gas entry into the wellbore. Any fluid loss below the filter-cake bridge or set cement results in a loss of trapped pressure, and this pressure loss is a function of fluid compressibility. Since most fluids are relatively imcompressible, a small volume change results in a large pressure change. For example, a Class H Cement slurry mixed to 15.7ppg slurry weight will drop in pressure from 5500 psi to 5000 psi with a filtrate loss of only 0.0009 cu ft per one cubic foot of slurry, Fig. 1. Thus, a filtrate-loss additive would be put to an extreme test to maintain trapped annular pressure over the fluid life of a cementing composition by filtrate-loss prevention. Carter and Slagle[3] have shown that only 1 psi pressure differential from formation to cemented annulus is required to initiate gas flow.

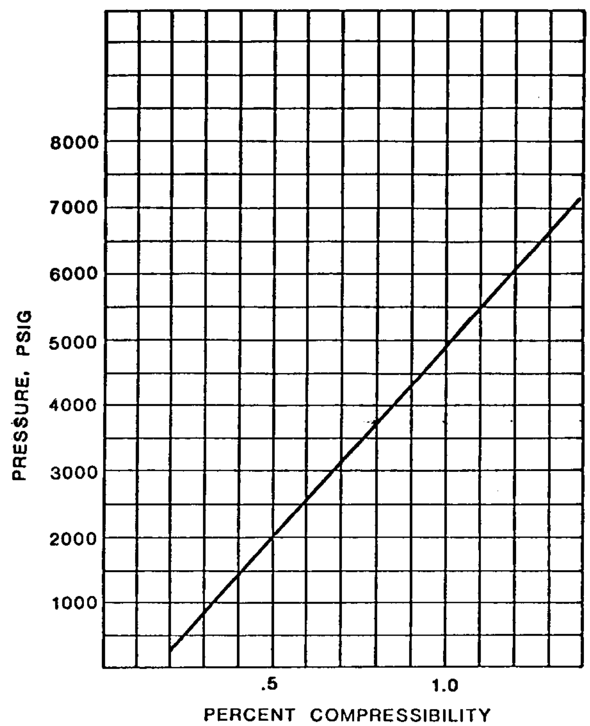

FIG. 1 –PERCENT COMPRESSIBILITY VS PRESSURE (15.7 PPG CLASS H CEMENT SLURRY)

A popular industry belief is that once cement has reached initial set the function of a fluid-loss additive has been fulfilled. Laboratory tests have shown that gas will displace water from cement which has taken an initial set creating microcapillaries, a permanent passage for gas migration.[9] These same studies indicated cementing formulations containing filtrate-loss-control additives are not as susceptible to developing permeability as are those containing no filtrate-loss additive. Further, increasing concentrations of fluid-loss additive resulted in less gas invasion and lower cement permeability. Gas pressure applied to the cement at final set (API Gilmore Test) indicated gas invasion, but not to the extent as at initial set.

DESIGN METHOD FOR FLUID-LOSS-CONTROLLED CEMENTING

The method proposed here attempts to design cementing slurries with sufficient fluid-loss control to prevent annular bridging due to dehydration of the slurry before a set is achieved. A considerable amount of information on well conditions is required to allow calculation of the maximum allowable filtrate-loss rate. This information includes:

1. Zone pressures
2. Zone depths
3. Fluid weights
4. Pump rate
5. Hole and pipe dimensions
6. Temperature
7. Filtrate-volume to cake-volume ratio.

This data is first used to calculate the maximum filtrate-loss rates for complete dehydration. A computer program was prepared which performs the necessary calculations and gives the expected pressure differentials and fluid-loss values for a number of time periods. Several examples are shown later in this paper. Once the required fluid-loss rates have been calculated, the next step is to design a cement slurry which meets the requirements of adequate thickening time, fluid-loss control, and set time.

Fluid-loss test procedures are considerably different from the normal API fluid-loss test. The filter medium is a formation section rather than a 325 mesh screen. A mud filter cake is first deposited on the formation and then removed by washing or mechanical means, hopefully simulating the condition of the formation downhole when the cement is placed across it. It should be noted that although it may seem desirable to use a formation similar to that in the well, previous work[9] has shown that cement fluid-loss is not greatly affected by the permeability of the formation, but more by the fluid-loss characteristics of the slurry and the pressure. The fluid-loss test pressure should be the same as the highest differential pressure anticipated across any zone when the cement is in place.

The filtrate should be measured at intervals until the filtrate production stabilizes sufficiently to allow extrapolation of the fluid loss for longer periods of time. From the area of the formation used in the fluid-loss test and the extrapolated fluid losses, the filtrate-loss rate over the set time of the slurry may be determined. If this rate is higher than the previously calculated maximum filtrate-loss rate, it is possible that the cement slurry may be totally dehydrated and bridge the annulus.

To illustrate the magnitude of fluid-loss control required to prevent annular bridging due to dehydration of the cement slurry prior to set under typical conditions, the following examples will be used:

Example No. 1

Well conditions include: a 7-ft liner in 9-7/8 in. hole from 15,000 ft to TD of 16,000 ft; cementing rate of 8 BPM; and 11.5 ppg drilling mud.

Permeable zones were at the following depths and formation pressures:

Zone 1 - 15,300 ft, 7680 psi
Zone 2 - 15,550 ft, 8500 psi
Zone 3 - 15,850 ft, 9200 psi

These conditions are shown in Fig. 2.

The highest annulus-to-formation pressure differential exists at Zone 1. Since the fluid loss is determined to a great extent by the differential pressure, Zone 1 is the point at which total dehydration is most likely to occur. If bridging were to occur at this point, Zone 2 may accept enough filtrate to lower the annular pressure at Zone 3 to less than formation pressure, thereby allowing gas to enter from Zone 3. The basis for the design of a fluid-loss-controlled cementing slurry is to maintain sufficient fluid-loss control to prevent bridging across the most troublesome zone, Zone 1.

For this example, if the second slurry in Table 1 with a filtrate-volume to cake-volume ratio of 0.475,

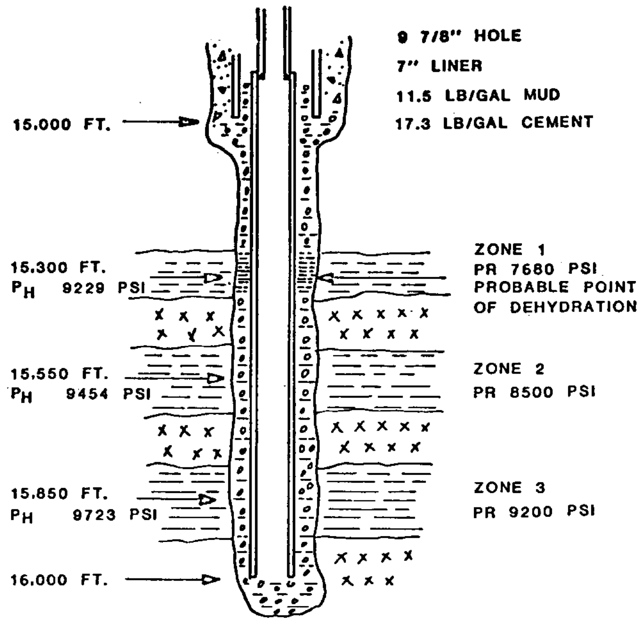

FIG. 2—FILTRATE CONTROL PRIOR TO CEMENT SET

is used as the cementing composition, the computer calculations, as shown in Table 2, indicate a maximum fluid-loss rate of 0.267 x 10^{-3} ft^3/ft^2-min to be required to prevent dehydration and bridging across Zone 1 with a 3-hr set time. This value for the maximum fluid-loss rate would be equivalent to a laboratory fluid loss of 23.4 cc in 3 hr at 1549 psi on a formation with an area of 16 cm^2.

TABLE 2—EXAMPLE 1

Zone No.	Depth Ft.	Pressure - PSI Hydrostatic	Formation	Differential
1	15,300	9229	7680	1549
2	15,550	9454	8500	954
3	15,850	9723	9200	523

Zone No.	Maximum Fluid Loss Rate - Ft^3/Ft^2-Min. 3 Hours	4 Hours	5 Hours	6 Hours
1	.267 x 10^{-3}	.201 x 10^{-3}	.161 x 10^{-3}	.134 x 10^{-3}
2	.265 x 10^{-3}	.200 x 10^{-3}	.160 x 10^{-3}	.134 x 10^{-3}
3	.263 x 10^{-3}	.198 x 10^{-3}	.159 x 10^{-3}	.133 x 10^{-3}

Example No. 2

For this example the same well conditions will be used as in Example 1, but the cementing slurry will be changed. In this case, the fourth slurry in Table 1 will be used. This slurry has a considerably higher filtrate-volume to cake-volume ratio than did the first slurry, 1.108 compared to 0.475.

The results of the calculations using this slurry, shown in Table 3, give a much higher allowable fluid loss of 0.624 x 10^{-3} ft^3/ft^2-min. at 3 hr. Again, this would be equal to a laboratory fluid loss of 54.7 cc in 3 hr.

TABLE 3—EXAMPLE 2

Zone No.	Depth Ft.	Pressure - PSI Hydrostatic	Formation	Differential
1	15,300	9167	7690	1487
2	15,550	9340	9500	840
3	15,850	9547	9200	347

Zone No.	Maximum Fluid Loss Rate - Ft^3/Ft^2-Min 3 Hours	4 Hours	5 Hours	6 Hours
1	$.624 \times 10^{-3}$	$.469 \times 10^{-3}$	$.376 \times 10^{-3}$	$.313 \times 10^{-3}$
2	$.619 \times 10^{-3}$	$.466 \times 10^{-3}$	$.374 \times 10^{-3}$	$.312 \times 10^{-3}$
3	$.613 \times 10^{-3}$	$.463 \times 10^{-3}$	$.372 \times 10^{-3}$	$.311 \times 10^{-3}$

Example No. 3

In this case, the same cementing slurry as in Example No. 1 will be used and the well conditions will be the same, except that the liner size is 5-1/2 in. instead of 7-in. in the 9-7/8 in. borehole. The results of the calculations for these conditions shown in Table 4 indicate a maximum fluid-loss rate of 0.369 x 10^{-3} ft^3/ft^2-min. for 3 hr or a laboratory test rate of 32.3 cc in 3 hr.

TABLE 4—EXAMPLE 3

Zone No.	Depth Ft.	Pressure - PSI Hydrostatic	Formation	Differential
1	15,300	9229	7680	1549
2	15,550	9454	8500	954
3	15,850	9723	9200	523

Zone No.	Maximum Fluid Loss Rate-Ft^3/Ft^2-Min 3 Hours	4 Hours	5 Hours	6 Hours
1	$.369 \times 10^{-3}$	$.278 \times 10^{-3}$	$.223 \times 10^{-3}$	$.186 \times 10^{-3}$
2	$.365 \times 10^{-3}$	$.276 \times 10^{-3}$	$.221 \times 10^{-3}$	$.185 \times 10^{-3}$
3	$.361 \times 10^{-3}$	$.273 \times 10^{-3}$	$.220 \times 10^{-3}$	$.184 \times 10^{-3}$

As can be seen from these three examples, a number of factors, such as the filtrate-volume to cake-volume ratio of a slurry and the hole geometry, influence the maximum fluid-loss rate required to prevent bridging due to dehydration of the cement slurry. It should be pointed out that while a cementing composition with a high filtrate-volume to cake-volume ratio may seem desirable, as in Example No. 2, the increased water ratio may make it more difficult to achieve adequate fluid-loss control.

The fluid life of the slurry is also an important factor. The longer the set time of the slurry, the better the fluid-loss control must be to prevent dehydration.

LABORATORY TESTING CONSIDERATIONS

Laboratory testing the selected cementing slurry is the final step in filtrate-loss-controlled design. Does the slurry meet the average loss needed to prevent a dehydration bridge in the annulus? Is the slurry so retarded as to promote setting from the bottom up? Attempts to answer these questions by laboratory testing leads to a hazy gray area where technology and capability are uncertain.

As stated earlier, the temperature profile of the well may show the higher circulating temperature some distance off bottom. Evidence to this fact has been published.[6,7] Should this be true, then to promote cement setting from the bottom up would require almost continuous changing of cement retarder during the mixing operation as well as an exact knowledge of the circulating temperature profile of the well. Logistics of the cementing operation does not lend itself readily to infinite retarder variation, nor is a detailed temperature survey normally run on the well.

The objective of laboratory testing is to duplicate as nearly as possible the downhole conditions of filtrate loss during and immediately following cement placement. This objective dictates detailed knowledge of well conditions: (1) depth of zones; (2) permeability; (3) formation pressures; (4) drilling fluid properties; (5) temperatures; and (6) hole and pipe geometry. Core samples of the various permeable formations for filtrate-loss rate testing would be most desirable.

During drilling, the formations are exposed to the drilling fluid and a cake of drill solids is formed. Attempts are made prior and during cementing to remove this cake to achieve a better bond. Mechanical means such as wall cleaners are employed; chemical washes and spacers, pipe movement, and placement of cement at turbulent rates all affect the formation face to some degree. At this time, laboratory equipment and technology do not allow exact duplications of downhole conditions at the time of cementing; an educated guess is made and testing proceeds on that basis. Do you coat the filter medium with mud and leave it or scrape it off? After scraping do you wash with running water? Lightly brush under running water? The question really is, to what degree has the mud cake or solids sealed the face of the formation, as this will bear on the rate of filtrate loss.

Laboratory filtration equipment is also limited for this type testing. Most of such equipment is designed for 1000 psi differential pressure, and only a limited number of such instruments in use will function at 2000 psi. Most of the apparatus is designed for the API static test with the 325 mesh screen and will not accept core wafers. Much improvement in test equipment and technology is needed to fully utilize this concept of designed filtrate-loss cementing.

CONCLUSIONS

1. A method of calculating the allowable filtrate-loss rate from a cementing slurry during various stages of cementing has been presented.
2. The presence of mud filter cake limits the rate of filtrate loss from a cementing slurry.
3. Filtrate-loss rates are controlled within the slurry and slurry filter cake and are affected to only a minor degree by formation permeability.
4. Without fluid-loss control, cement slurries may fail to transmit full hydrostatic pressure even before the initial set.
5. Gas differential pressure applied to initial or final set cement with high filtrate-loss characteristics may result in microcapillaries. Low fluid-loss slurries maintained low permeability.
6. Maximum fluid-loss control in cementing slurries should be used to minimize gas leakage when cementing across zones of varying pressure.

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