# Controlling Flow After Cementing

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## Abstract

Annular water and gas flow after cementing, along with poor mud displacement, have long been recognized as key potential failure mechanisms during primary cement operations.  Many technical papers have explored solutions to these post-cementing flow problems.   Some authors have suggested shortening or delaying the start of transition time.  Others have discussed fluid loss control, static gel strength development, particle packing, and even mechanisms of downhole gas generation.

In this paper, we will underscore the value of those techniques, both for gas migration control and displacement efficiency, while offering an entirely new solution to be applied in combination with the operator's preferred prevention methodology.  We believe this combined approach will enhance the overall success of the well construction process and improve long-term outcomes.  The subject new technology acts independently of current methodologies, so there is no potential for interference.

The paper will include a case history to demonstrate the effectiveness of this new approach through comparisons of field results with other wells in the area.

## Gas Migration and Cement Gel Strength

Annular 'fluid' (gas or water) flow following primary cementing has long plagued the industry. As early as 1972, Johnson and Garvin in "Cementing Practices" mentioned problems associated with flow behind the casing after cementing as being an industry problem.  In their 1974 paper, Stone and Christian recognized the problem was related to something occurring with the unset cement.  In January of 1976, Garcia and Clark wrote the paper "An Investigation of Annular Gas Flow Following Cementing Operations."  November of the same year, Christian et al. published a field and laboratory study on "Gas Leakage in Primary Cementing."  By 1980, the basics behind gas migration were beginning to be understood with the Tinsely et al. paper.  In 1982, Sabins et al. coined the phrase 'Transition Time,' which plays a vital role in today's understanding of the problem.

Prior to spudding the well, during the drilling process, and continuing throughout the cementing process, the pore pressure ($P_p$) of the gas or water-containing zone remains relatively constant unless the fluid volume of this interval is very minimal.  One of the many purposes of the drilling fluid is to provide sufficient overbalance to keep the formation fluid in place, in the formation.  As long as the mud weight is kept above the highest pore pressure encountered, the formation fluid will stay in the formation.

The density of the cement spacer is typically equal to or greater than the mud weight (MW).  The cement density is then even greater than that of the spacer.  If the combined column weight is higher than what was used to effectively control the well while drilling, the higher cementing weight should be sufficient to control the fluid from flowing into the annulus during cementing.   The fact is that this initial overbalance pressure has consistently proven insufficient at preventing annular gas migration.  Understanding why the problem is occurring is much easier than eliminating or preventing gas or water flow up through the annular space on the backside of the casing.

To understand this phenomenon of gas migration, one must understand basics of fluid flow, fluid dynamics, and physics.  When the annular space of a wellbore is fluid-filled, the static wellbore pressure ($P_{hyd}$) at any point is the sum of the weights of all of the fluids above that point, plus the local atmospheric pressure ($P_{atm}$) or the back-pressure ($P_{bp}$) being applied.  If just the drilling fluid is present,

$$P_{hyd} = P_{atm} \text{ (or } P_{bp}) + MW * TVD * \text{Conversion Factor} \quad (\text{Eq. 1})$$

If there are multiple fluids in the wellbore, the MW * TVD would be replaced with the summation of each fluid's density multiplied by their True Vertical Length (TVL).   This summation is often referred to as hydrostatic pressure ($P_{hyd}$).  A key concept in understanding gas migration is that $P_{hyd}$ is only a fluid property and not a solid property.

At the completion of the cement job, the column which can be pure cement (including multiple types), cement and spacer (including multiple types), or a combination of cement, spacer, and mud will behave as a true fluid. $P_{hyd}$ will be reflected by the above equation and can be calculated at any potential gas invasion depth.

Typically, in less than 24 hours, the cement will be set and the ability to transmit $P_{hyd}$ will be lost.  At some point in time, during that approximately 24-hour window, either the cement has become set enough or thick enough that the gel strength of the cement is sufficiently high to prevent fluid migration from starting if it has not already begun.  If so, this cement job can be deemed successful, at least from a gas migration prevention point of view.

It is important to understand the terms, 'thick enough' or 'set enough'. If at some point $P_{hyd}$ becomes less than $P_p$, the pore fluid or gas that is pressurized to $P_p$ will enter the annulus. This invasive fluid or gas can move up or down the annulus. If it is heavier than the annular fluid, it will move down. If it is lighter than the annular fluid, it will move up. Since we are discussing gas or water vs. cement, buoyancy will cause this invading (lighter density) fluid to try and move upwards.

The next question becomes, does this invading fluid just barely push its way into the annulus, or does it freely flow upward? To answer that question, we must understand why it might not. Remember, buoyancy is the driving force to allow the lighter density fluids to flow up the annulus. For as long as the cement remains in the liquid state, the force countering gravity is friction, or the gel strength of the cement, resisting the upward motion of the formation gas or liquid. For the gas bubble or liquid droplet to migrate up, it must pass through the annular cement fluid of higher density.

At the moment the pumping concludes, thus terminating the cement job, the fluid is thin enough that it will provide little resistance to the upward migration of any invading fluid. Or in other terms, if the cement density is less than the formation pressure ($P_p$), gas will migration into the wellbore. The period is referred to as the 'zero gel time' and cement has little gel strength to resist flow.

After some time, which can vary from a few minutes to a few hours, the cement will begin to develop static gel strength, which can restrict the transmission of full hydrostatic pressure. At this point, the cement is said to have started the transition time (Sabins et al. 1982).

As time passes and the gel strength builds, the resistance to flow increases. Eventually, the gel strength reaches a level where the frictional force exceeds the buoyancy forces. The buoyancy force will no longer be capable of pushing the slurry apart and the invading fluid will not rise up through the annulus. This means if fluid migrates up through the cement column has not already begun, it will not start after the gel strengthens. This period is known as the 'end of the transition time.'

Although the transition time can vary for every cement type and job, Sabins et al. (1982) defined the transition time as the length of time the slurry takes, under static conditions, to progress from the point where 100 lb/ft$^2$ of gel strength is observed until 500 lb/100 ft$^2$ of gel strength is reached (or the end of the transition time).

In the initial lab testing, single cement samples were split into two. One half went into the original HPHT static gel strength measuring device, and the other half was introduced into a length of pipe. At various fixed levels of gel strength measured on the sample, in the static gel measuring device, gas was introduced into the bottom of the pipe containing the partially gelled cement. If gas percolated to the top, the test was terminated. A new cement sample was made and the test repeated, with gas being introduced at higher and higher levels of gel strength until the gas introduced into the annular space did not migrate to the top of the column.

The next piece of the puzzle is understanding how gel strength contributes to the loss of pressure, and where the

pressure goes. Prior to the start of the transition time the wellbore is more or less an open system. Small amounts of volume loss are relatively meaningless. The developing gel strength is what creates the closed system. In a closed system with a incompressible fluid, small amounts of volume loss can contribute to a large pressure loss. This potentially problematic pressure reduction that occurs as the cement dries, or moves from liquid to solid phase, is caused by two mechanisms.

The first mechanism is the standard hydration reactions that are associated with the physical solidification of the cement. As water is 'consumed' in the hydration reactions, the absolute volume of the system decreases, i.e., the cement "shrinks" in volume. With the cement slurry being a relatively non-compressible fluid, in a closed system, even a relatively small volume reductions can contribute to a large pressure reduction.

The second mechanism is fluid loss. As the cement is sitting static in the annular space with a higher density than the surrounding pore pressure, small amounts of liquid are leaking out of the cement system and into the surrounding rock, microfractures, faults, sands, bedding planes, etc. Again, with the cement slurry being a relatively non-compressible fluid, in a closed system, these small volume reductions can contribute to a large pressure reduction. If a low fluid loss cement is utilized, these volumes are relatively insignificant (see Equation 1). The $P_{hyd}$ calculated in this method assumes a true fluid and a continuous system. Once the cements begins building gel strength, it can support some of the load, or a pressure differential. Thus, these volume losses will now contribute to a pressure loss. Again, in an open system, small volume losses will not contribute much to a hydrostatic change. However in the closed system, with an incompressible fluid, these changes can be significant. If the $P_{hyd}$ falls below the $P_p$ before the cement gets so thick as to prevent flow by friction or viscosity alone (before the end of the transition time), fluid flow can commence.

This creation of a closed system was proven in a case study by Cooke et al. (1983). In their experiment, they attached several pressure gauges to the outside of a casing string. After completion of the cement job, they immediately applied back-pressure. This pressure change was observed on all gauges. Periodically, additional pressure was applied. As the cement began to gel, transmission of this pressure was inhibited. Eventually the effect of additional surface back-pressure was only observed by the sensor above the top of cement.

Traditional anti-gas migration solutions have focused on:
- Reducing fluid loss (reducing the volume losses)
- Using thixotropic slurries (shortening the transition time, getting us to the safe point sooner)
- In-situ volume generation (replacing lost volume)
- Increasing slurry compressibility (each unit of volume lost corresponds to a smaller unit of lost pressure than with incompressible slurries)

With minor gas flow issues, any one of these options may be enough to safely cement the annular space. With more severe wellbore conditions, several of these options are typically utilized.

Another option to stop gas migration is based on the theory that if the slurry design contained some system whereby a chemical or mechanical reaction were to occur to separate the cement and the invading formation fluid or gas, that could also be used to halt the invasion.

## Wellbore Shield Spacer

The spacer used in this paper's case history is unique in the industry because of its inherent ability to create a barrier or wellbore shield (WBS) between the formation fluids and the wellbore fluids stopping the flow into the annulus.  Spacers are pumped ahead of the cement, in order to separate the mud and the cement. Typically, the mud and cement are highly incompatible, and spacers to help push the mud out of the wellbore, allowing an easy path for the cement to fill the annular space to the planned level.   With the WBS spacer, non-damaging microparticles are deposited on the inside face of the wellbore.  In both slot testing and sand bed testing it can be shown that this barrier is relatively impermeable, forming both a pressure and fluid/gas barrier. The WBS spacer not only mitigates the invasion of formation fluids, but also improves the cement-formation bond at the wall. A unique mechanical characteristic of this system is in the way these microparticles lock together with differential pressure, holding them together and in-place on the wellbore face.  It has been well established (Metcalf et al. 2011; Samuel et al. 2016; Kulakofsky et al 2018; Bermudez and Doria 2018; and Jordan et al. 2019) that this barrier can allow successful cement circulation in situations where the equivalent circulating density (ECD) limitations would normally be associated with incomplete returns.

## Displacement Efficiency

Many papers have been written about what basics are required during a cement job to achieve effective mud displacement (Jordan et al. 2019; Smith 1990; Haut and Crook 1979).  Most of recommendations for achieving a good cement job focus on these basic rules of thumb:

- Sufficient pre-job mud conditioning should be provided to get the wellbore ready to receive cement. Bottoms-up twice is a decent rule of thumb.
- Centralize the pipe through the cemented interval to a standoff of at least 70%. Eccentricity of the pipe in the annulus can prevent cement flow from reaching all areas, especially the narrowest gaps between pipe and wellbore wall.
- Rotate or reciprocate the pipe while the cement is rising up the annulus. Rotation can help make up for poor standoff.
- Pump plenty of a spacer that has been engineered to be thick enough to displace any non-mobile mud.  Design for 12-15 minutes of contact time as a rule of thumb.
- The cement job should be displaced as fast as possible, without losing circulation.

## Case History: Llano Orientales Basin

While drilling the top-hole section during the rainy season,

a water influx was experienced; this typically occurs when drilling wells near the rivers in the Llano Orientales Basin in Colombia.  In wells where this water flow occurs while drilling, the water flow re-appears post-cementing (following surface casing cement jobs).   This post-cementing water flow had previously proven impossible to prevent or control during remediation.  When post-cementing water flow occurs, top jobs become necessary.   Moreover, these top jobs are rarely successful, resulting in non-productive time (NPT) and additional costs.  With uncontrollable water flow, additional operating expenses are required to bleed off the water pressure periodically.  There is also a high likelihood of pipe corrosion, which will shorten the life of the well.  Thus, it is critical that the water flow can be controlled with the primary cement job.

While drilling the 17½-in section in one of these Llanos Orientales Basin wells, the seasonal water flow was measured at a rate of 1,680 bbl/d (70 bbl/hr), in the case history well.  In this well, the water flow was encountered at a depth of 200 ft.  In an attempt to minimize the water flow, a densified 15-lb/gal mud pill was utilized.  Once the flow was controlled, drilling resumed with an 11.2-lb/gal mud weight to the programmed surface casing depth of 2,100 ft.

To keep this water flow under control during and post-cementing, the following practices were implemented:

- Do not begin the cement job until the water flow is under control with no observed in-flux.
- Design the cement slurries with as short as possible transition time.
- Follow best displacement and cementing practices
- Implement a rheologically optimized WBS spacer to help the cement bond to the formation.  Further, the impermeable barrier formed by this WBS spacer on the inside face of the formation will eliminate or drastically reduce any fluid loss from the cement. By reducing or eliminating losses from the cement, the annular pressure can be maintained, and flow prevented.
- Perform a top job immediately after finishing the primary cementing job.

Upon completing the cementing job, the annulus was monitored for flow.  No flow was observed.  The floating equipment was drilled and an integrity test performed as per the drilling program.  The pressure remained stable, indicating good cement integrity in the area of the shoe.

In 2019, out of the 30 wells drilled in this region, three wells experienced this type of rainy season, river-induced flow while drilling.  The first two wells were cemented using conventional best practices, and failed to prevent flow after cementing.  The third well, the case history described in this paper,  successfully combined conventional best practices and the WBS technology.

In addition, to the surface string where the post-cementing water flow was alleviated, the WBS spacer was used to help cement three 7-in. production strings.   The displacement efficiency had been less than ideal while cementing the production strings, as indicated by poor bond logs.  The final three production strings utilizing this rheologically optimized WBS spacer achieved good bond logs.  This WBS spacer is

programmed for the production strings on all 20 wells planned for 2020, as well as any surface strings that encounters water flow while drilling.

## Conclusions

Focusing on stopping the water influx into the annulus resulted in a good cement job and eliminated NPT and costs that would have been resulted from the poor cement job typically achieved with the rainy-season water influx.

A key to eliminated post cementing fluid flow is maintaining sufficient annular pressure during the entire transition time.

A WBS spacer is proven to create a barrier between formation fluids and annular fluids. The WBS microparticles are depositing at the wellbore wall and locked together by differential pressure.

A WBS spacer will help control annular flow when paired with good cementing practices.

## Nomenclature

HPHT = high pressure, high temperature
MW  = Mud weight
$P_p$   = Pore pressure
$P_{atm}$  = Atmospheric pressure
$P_{bp}$   = Backpressure  The annular flow can be choked back, thus applying a backpressure to the well
$P_{hyd}$  = Hydrostatic pressure at any depth
TVD  = True vertical depth
TVL  = True vertical length

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