Five years ago, an article in Oilfield Review stated, “Understanding gas intrusion is an evolutionary process that has not yet run its full course.” Since then, the evolution has continued, providing a more detailed picture of the downhole phenomena active during gas migration. Although many possible solutions are similar to those available in 1991, increased knowledge of gas entry mechanisms means that these solutions can now be deployed in a more logical and cost-effective way.

Gas invasion occurs when pressure is lower in the annulus than at the formation face. Gas then migrates either to a lower pressure formation or to the surface. The severity of the problem may range from residual gas pressure of a few psi at the wellhead to a blowout. Whatever the severity, the major factors contributing to gas migration are common. Successfully achieving a long-term annular cement seal begins by understanding these contributing factors.

For help in preparation of this article, thanks to Art Milne, Dowell, Clamart, France and Tom Griffin, Dowell, Sugar Land, Texas.

CemCADE, GASBLOK, GASRULE, VIP Mixer and WELLCLEAN are marks of Schlumberger. MicroVAX is a trademark of Digital Equipment Corp.
Fluid densities are too high. Also, consideration must be given to the free-fall or U-tubing phenomenon that occurs during cement jobs. Therefore, cement jobs should be designed using a placement computer simulator program to assure that the pressure at critical zones remains between the pore and fracture pressures during and immediately after the cement job.

Any density errors made while mixing a slurry on surface may induce large changes in critical slurry properties, such as rheology and setting time. Inconsistent mixing also results in placement of a nonuniform column of cement in the annulus that may lead to solids settling, free-water development or premature bridging in some parts of the annulus. This is why modern, process-controlled mixing systems that offer accurate density control, mud removal and slurry design—are critical, and here is why.

Density: Controlling the driving force—Gas can invade and migrate within the cement sheath only if formation pressure is higher than hydrostatic pressure at the borehole wall. Therefore, as a primary requirement, slurry density must be correctly designed to prevent gas flow during cement placement. However, there is a danger of losing circulation or fracturing an interval if fluid densities are too high. Also, consideration must be given to the free-fall or U-tubing phenomenon that occurs during cement jobs. Therefore, cement jobs should be designed using a placement computer simulator program to assure that the pressure at critical zones remains between the pore and fracture pressures during and immediately after the cement job.

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Density control are proving popular for critical cement operations (left).

A cement slurry will not transmit hydrostatic pressure forever. The transition from a liquid that controls formation pressure to an impermeable solid is not instantaneous. Consequently, there is a period during which cement loses the ability to transmit pressure. No matter how carefully a slurry has been designed to counterbalance formation pressure, it will not necessarily resist gas invasion throughout the hydration process.

Mud removal: No easy paths for gas—If channels of mud remain in the annulus, the lower yield stresses of drilling fluids may offer a preferential route for gas migration. Furthermore, water may be drawn from the mud channels when they come into contact with cement. This can lead to shrinkage-induced cracking of the mud, which also provides a route for gas to flow. If the mud filter cake dehydrates after the cement sets, an annulus may form at the formation-cement interface, thus providing another path for gas to migrate. For example, a 2 mm (0.08 in.) thick mud filter cake contracting by 5% will leave a void 0.1 mm (0.004 in.) wide that has a "permeability" on the order of several darcies.

Cement slurry design: Mixing the right stuff—Fluid-loss control is essential. Under static conditions following placement, uncontrolled fluid loss from the cement slurry into the formation contributes to volume reduction. This reduces pressure within the cement column and allows space for gas to enter.

Before the cement slurry sets, interstitial water is mobile. Therefore, some degree of fluid loss always occurs when the annular hydrostatic pressure exceeds the formation pressure. The process slows when a low-permeability filter cake forms against the formation wall, or can stop altogether when annular and formation pressures equilibrate. Once equilibrium is reached, any volume change within the cement will cause a sharp pore-pressure decline in the cement slurry or the developing matrix, and severe gas influx may be induced. Poor fluid-loss control in front of a gas-bearing zone may accelerate the decrease in cement pore pressure. It is equally important to have a cement slurry with low or zero free water, particularly in deviated wells. As cement particles settle to the low side, a continuous water channel may be formed on the upper side of the hole, creating a path for gas migration.
How Gas Gets into the Annulus

Understanding the mechanisms of gas migration is complicated by the evolution of the annular cement column with time. The slurry begins as a dense, granular suspension that transmits full hydrostatic pressure. As the slurry gels, a two-phase material is formed that comprises a solid network with pore fluid forms. Finally, the setting process reaches a point where the cement is for all intents and purposes an impermeable solid. After slurry placement, gas may enter through different mechanisms according to the evolution of the cement's state, the pressures it experiences and other wellbore factors.

Cement state 1: Dense granular fluid—When pumping stops, the cement slurry in the annulus is a dense, granular fluid that transmits full hydrostatic pressure. If formation pore pressure is not greater than this hydrostatic pressure, gas cannot invade. However, almost immediately, pressure within the annulus begins to fall because of a combination of gelation, fluid loss and bulk shrinkage.

This pressure reduction is best described by the evolution of a wall shear stress (WSS) that begins to support the annular column as the cement slurry gels. In order for a stress to evolve to counteract the hydrostatic pressure, there must be a vertical or axial strain at the annulus walls. This strain is caused by the removal of material during the hydration and setting processes—primarily through fluid loss and shrinkage.

If it is assumed that WSS equals the static gel strength (SGS) of the slurry and there is sufficient axial strain, the following simplified expression can be used to describe hydrostatic pressure reduction during gelation:

$$\Delta P = \frac{SGS \times 4L}{D_h - D_c}$$

where $\Delta P$ = hydrostatic pressure change across column length

$SGS$ = static gel strength

$D_h$ = hole diameter

$D_c$ = casing outside diameter (OD)

$L$ = cement column length.

As the cement sets, static gel strength constantly increases, with the rate of increase dependent on the nature of the slurry. There is potential for gas invasion once pressure in the annulus falls below the pressure in the gas-bearing formation. Even with a mud filter cake between the formation and cement, a differential pressure of less than 1 psi may allow gas to invade. The resistance of an external filter cake to gas flow is controlled by the cake's strength and adhesion to the rock face, which both have relatively low values for drilling fluids and neat cements.

This explains the driving force of gas invasion, however, there must also be space within the cemented annulus for gas to occupy. Space is provided by shrinkage, which occurs because the volume of the hydrated phase is generally less than that of the initial reactants. This total shrinkage is split between a bulk or external volumetric shrinkage, less than 1%, and a matrix internal contraction representing 4 to 6% by volume of cement slurry.

Permeability is a more complicated issue. Once gelation begins, a cement slurry can be considered as a pseudoporous medium as long as the stress that it must withstand from formation fluid is less than its intrinsic strength. Thus, even though a partial structure has been formed and the cement column is not yet fully self-supporting, with regard to its flow capacities, it can be said to have permeability.

Cement slurries display an evolving yield stress that must be overcome before gas entry and flow can occur. Depending on the state of the slurry, gas can migrate by micropercolation, bubbles or fractures. Opportunity for gas entry decreases as the cement cures. The rate and degree of yield stress development at the time of invasion will influence the form in which gas flows. Gas may enter and flow through the porosity of the gelling structure without disrupting it—micropercolation. Gas may also move by disrupting the gel structure in the form of bubbles or elongated slugs, in channels along the interfaces with the casing and formation or as bubbles which adhere to one of the surfaces of the annulus. If rising gas remains connected to the influx source it may form a plume as it moves through the cement slurry (above).

The size of gas bubbles entering the annulus is governed by the size of the cement pore throats and the surface tension between the gas and the slurry. Once bubbles have invaded the annulus, their lower density provides a driving force—buoyancy—for them to move up the annulus through any available path. Bubble flow is controlled by slurry gel strength, and is restricted to early in slurry development. When cement shear strength is greater than about 25 Pa, bubble flow ceases.

At higher yield stress values, slurry behavior changes from that of a viscous fluid to a viscoelastic fluid, and the possibility of flow by viscous fingering or viscoelastic fractures arises. The differential pressure—between

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6. Geometry separates fingering and viscoelastic fractures. A fracture has a sharp tip; a finger has a smooth tip. This difference is determined by a fractal length scale that is associated with the fracture or finger geometry.
annulus and formation—combines with the developing elasticity of the cement to determine the rates of deformation and internal relaxation. The relative values of these determine the transition from fingering to fracture. The transition to fracture is exacerbated if the cemented annulus contains an internal tensile stress caused by the strain of shrinkage, fluid loss or pressure fluctuations in the casing. Gas may then drive the propagation of fractures and lead to a rapidly extending gas channel. Hydrostatic pressure will continue to decline as static gel strength—and resultant wall shear stress—develop sufficiently to support the weight of the cement column. The cement has now reached its second state.

Cement state 2: A two-phase material—Once a cement column becomes fully self-supporting, it may be considered to act as a matrix of interconnected solid particles containing a fluid phase. Setting continues and hydration accelerates. Pressure, now a pore pressure, decreases further as cement hydration consumes mix water. This leads to an absolute volume reduction or shrinkage of the internal cement matrix by up to 6%. Furthermore, the majority of shrinkage occurs at this stage, leading to tangential tensile stresses in the annulus, which may assist the initiation of fractures and disrupt bonding between the cement and the casing or formation.

Internal shrinkage creates a secondary porosity in the cement composed mainly of conductive pores. At the same time, the volume of water continuously decreases due to hydration, and its ability to move within the pores is reduced by chemical and capillary forces. Shrinkage and water reduction sharply decrease the hydrostatic pressure that cement exerts on formations.

There are two essentially different mechanisms for gas invasion at this stage, depending on the strength of the solid structure and the ease with which pore fluid can be forced through the cement pores by invading gas. Early in the setting process, while the cement still has a weak solid structure, the possibility of creating fingers or viscoelastic fractures remains. Later, the solid network becomes sufficiently stiff and strong to withstand this effect, and gas invasion and subsequent flow are limited by the impermeability of the solid network to pore fluids. Now, the flow of gas through a channel of connected, fluid-filled cement pores is limited by the flow of that pore fluid as it is displaced through the porous structure and by the connectivity of the channel (left).

Once gas has invaded the porous structure of the cement, it may rise due to buoyancy forces. Alternatively, if the invading gas remains connected through the cement pore space to the gas-bearing formation, the higher pressure in the formation may force gas farther into the annulus. If gas pressure is higher than the minimum compressive stress in the cement and the permeability is too low to allow significant flow, then the cement may fracture. However, this is likely to occur only where residual tensile stresses in the annulus are sufficiently high to allow cracks to open under the influence of the gas pressure.

During the latter stages of this phase, there is a significant and rapid decrease in pore pressure as water is further consumed by hydration. If this occurs while the pore structure is still interconnected, gas may invade and flow rapidly through this pore space (next page). Gas flow may also displace fluid remaining in the pores and prevent complete hydration that would eventually block pore spaces with reaction products.

Cement state 3: An elastic solid—Once hydration is complete, cement becomes an elastic and brittle material that is isotropic, homogeneous and essentially impermeable. In most cases, gas can no longer migrate within the cement matrix and can flow only through interfacial channels or where there has been mechanical failure of the cement.
Regardless of the cement system used, gas can still migrate at the cement-formation or cement-casing interfaces if a microannulus develops, or along paths of weakness where the bond strength is reduced. Both shear and hydraulic bond strengths vary as a function of the same external parameters. Bond strengths increase with effective mud removal, and with water-wet rather than oil-wet surfaces.

Researchers at Schlumberger Cambridge Research (SCR) have characterized the nature of hydraulic bonding by measuring shear bond stress and interfacial permeability. This work showed that lower chemical shrinkage and higher cement deformability promote better bonding. In addition, SCR researchers found that bonding is not influenced by the cement’s compressive strength.

Although cement shrinkage leaves partially unbonded areas, it does not by itself lead to the development of a microannulus. Development of a true microannulus more likely results from stress imbalances at the interfaces due to:

- thermal stresses— from cement hydration, steam or cold fluid injection
- hydraulic pressure stresses— caused by fluid density changes in the casing, communication tests, casing pressure tests, squeeze pressure or stimulation treatment pressures
- mechanical stresses— caused by drillpipe and other tubulars banging in the casing.

The second potential conduit for gas in set cement is the mechanical failure of the cement sheath due to propagation of radial fractures or cracks across the annulus. These cracks may be due to shrinkage-induced stresses, thermal expansion and contraction of the casing, and pressure fluctuations within the casing.

Radial expansion at the cement-casing interface, due to increased pressure in the casing, creates a stress that compresses the cement radially and eventually induces tensile tangential stress in the cement. When

Changes in slurry permeability, pore pressure and temperature versus hydration time. These graphs show that cement pore structure is still interconnected when pore pressure begins to decrease rapidly. In this Dykerhoff class G plus 1% calcium chloride slurry, pore pressure begins to drop after about 5 hours, just before the peak temperature of hydration is reached. When cement pore pressure drops below formation gas pressure, it is likely that cement permeability will still be in the millidarcy range, potentially allowing significant gas flow by micropercolation.

8. A limited exception to this may occur in the case of cement systems with high water-cement ratios, resulting in fairly high innate permeabilities (0.5 to 5 md). However, these are exceptional and not considered significant among those cements generally placed when a potential gas migration problem is thought to exist.
9. Deformability is the reciprocal of elastic modulus.
this tangential stress reaches the tensile strength of the cement—which may be close to zero if shrinkage-induced cracks already exist—a crack initiates at the casing-cement interface (below).

Cracks change the stress distribution in the cement sheath. Once a crack is initiated, tangential stress in the cracked section is reduced to zero. Conversely, stress in adjacent uncracked cement eventually increases because of stress redistribution. This process helps the crack propagate radially outward and eventually reach the cement-formation interface. Stress is now fully transferred to the cement-formation interface. If this cracking occurs over a significant axial distance, a channel is formed through which gas can readily flow.

Long-term cement durability is important if a well is to remain safe throughout its lifetime. During its active life, a cemented annulus may be subjected to wide variations of temperature and stress from pressure testing, workover operations and variations in producing conditions.

However, field surveys on gas storage wells—which endure some of the most extreme swings in conditions—determined that annular gas leakage occurs early, within the first few cyclic fluctuations in temperature and pressure, rather than over a long period. This implies that leakage occurs due to failure induced by static loads rather than long-term, low-cycle fatigue crack growth. Deeper and higher-pressure wells showed the greatest tendency to leak.11

The propensity of a particular cement to crack and for that crack to propagate has often been equated with compressive strength. In fact, work carried out at SCR shows that a property termed toughness determines the extent to which a cement slurry fractures under stress. Toughness is generally described in terms of the ability of a material to resist the initiation and subsequent propagation of a fracture. However, the situation is somewhat more complicated, since initiation and propagation of fractures are controlled by physical phenomena that differ, depending on the material’s structure (see “Compressive Strength Versus Toughness: A Brief Overview,” next page).

Using Theory to Define Best Practice
Over the years, a number of solutions to gas migration have been proposed by the industry. Theoretical understanding helps to explain how these solutions work—and their limitations.

**Physical techniques**—A number of physical techniques are available to combat gas entry. Annular pressure can be applied at surface to keep formation gas from entering, and external casing packers (ECPs) can be employed to mechanically seal off the annulus at intervals and prevent gas migration.

Each of these techniques may sometimes be valid, but well conditions often limit their application. Annular pressure may be restricted by the risk of inducing lost circulation in weak zones and, once the cement starts to set, surface pressure is not transmit-

ded to the formation. Alternatively, hole conditions and type of formation may not allow ECPs to seal the annulus. Furthermore, reduction of hydrostatic pressure through use of ECPs may enable more gas to immediately enter the slurry than would have been the case without ECPs (above).

**Impermeable cements**—Gas migration may be prevented by reducing the matrix permeability of cement systems during the critical liquid-to-solid transition. There are two approaches to achieving this: stop fluid from moving through the pores or close off the pores themselves.

The use of water-soluble polymers that viscosify cement interstitial water and reduce permeability within setting cement may be prevented by reducing the matrix permeability of cement systems during the critical liquid-to-solid transition. There are two approaches to achieving this: stop fluid from moving through the pores or close off the pores themselves.

The use of water-soluble polymers that viscosify cement interstitial water and reduce permeability within setting cement falls into the first category. Since at least a part of gas migration involves displacement of cement pore fluid, this viscosification can limit gas mobility. Unfortunately, the process also tends to affect slurry rheology, making it more viscous and raising the displacement pressure. This method is also usually limited to low-temperature applications because efficiency of viscosifiers decreases with temperature.

The second strategy of reducing the spaces in the cement matrix, preventing bubble entry and locking the fluids within the cement pore spaces, has proven more fertile. As a solid structure develops in setting cement, the smaller pore throats reduce

The compressive strength of a material describes the stress at which a material fails when a compressive load is applied (top right). When a compressive load is applied to a sample of brittle, elastic material such as cement, stress generally increases linearly with strain (displacement) until small microcracks and flaws in the sample begin to grow.

This is a progressive mechanism and manifests itself on the stress-strain plot by the change from linear proportionality between stress and strain to a softening section of the curve near the failure point. Once the cracks coalesce and reach a critical size, the sample will fracture via a complicated mechanism, which is determined by the boundary stress conditions and geometry of the sample.

Compare this with a description of cement toughness. Simplistically, toughness describes the property of the material to resist the initiation and propagation of a crack in a particular orientation.\(^1\) Fracture toughness is quantitatively defined as the energy required to propagate a fracture of unit width by unit length.

Without considering mathematical details, a reasonable indication of toughness for similar materials is given by the area (A) under the stress-strain curve to the failure point. This area varies according to the toughness of the material being tested.

For example, consider two materials X and Y that have the same compressive strength. The material X has a much smaller strain to failure than material Y, which contains latex. Therefore, material Y can deform further and absorb more energy before it fractures. Material Y is tougher than material X.

Data like these were gathered at Schlumberger Cambridge Research using three-point bend test equipment (right). The cement sample is placed on two lower static knife edges and the upper moveable knife edge is moved downward until the cement fails. The equipment is designed so that the sample always fails in tension. Strain (displacement) and load (stress) are recorded using computerized data recording systems.

\(^1\)Cement behavior under compression. The load or stress at which complete failure occurs defines the ultimate compressive strength of a material. Toughness, on the other hand, is an indication of the ability of a material to deform and absorb energy before fractures initiate and propagate.

\(^2\)Three-point bend test. This equipment is designed so that cement samples always fail in tension. Strain (displacement) and load (stress) are recorded using computerized data recording systems.
the size of bubbles that enter, slowing their subsequent rise—even when the yield stress of the cement is relatively low.

Polymer latex additives are effective in resisting gas migration. A latex is an aqueous dispersion of solid polymer particles, including surfactants and protective colloids that impart stability to the dispersion. In the past, the gas-blocking mechanism of latex additives was attributed to a capability to form films—when latex particles come in contact with a gas or when their concentration exceeds a given threshold value, they coalesce to form an impermeable polymer barrier to gas.

However, new work has revealed that latex particles are also able to block gas when the cement slurry has developed some structure or some compressive strength. This demonstrates that the primary effect of latex particles is matrix permeability reduction by plugging spaces between cement particles, rather than by the formation of an impermeable plastic film. Due to its smaller size and lower density compared to cement particles, latex reduces cement slurry porosity, improves fluid-loss control, decreases relative permeability to water and limits gas migration.

Right-angle-set cements—Right-angle-set (RAS) cement slurries are well-dispersed systems that show no progressive gelation tendency, yet set rapidly. Before setting, RAS systems maintain a full hydrostatic head on gas zones, developing a low-permeability matrix with sufficient speed to prevent significant gas migration.

It is important to differentiate between true RAS systems and cement slurries that only build a gel strength. The high-gel-strength systems quickly revert to a water hydrostatic gradient and, since their gel strength development is not related to actual setting, permeability can remain high for a considerable time. This may allow gas to enter the cement matrix many hours before the cement sets. On the other hand, RAS cement systems rapidly build consistency as a direct result of the setting process.

Surfactants—Surfactants may be included in cement slurries and preflushes. Under the right circumstances, they entrain invading gas downhole and create a stable foam. This foam offers significant resistance to flow, limiting upward gas migration.

Compressible cements—Compressible cements are sometimes used in an attempt to maintain the cement pore pressure above formation gas pressure. These slurries fall into two main categories: foamed cements and in-situ gas generators.

Foamed cements work by expanding to occupy the reduction in slurry volume due to fluid loss or chemical contraction. This

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The “ideal” slurry properties required to successfully withstand gas invasion include:

- favorable rheology to facilitate efficient placement
- no gel strength development to maintain hydrostatic balance
- rapid transition to set
- low shrinkage to minimize gas entry
- low fluid loss
- low permeability as the slurry sets
- toughness to absorb stress changes
- good bonding to avoid microannuli.

The Dowell GASBLOK gas migration control cement system combines specific additives and strict adherence to good cementing practices, including spacers and washes, and casing centralization. It has a wide range of applications and has had excellent success. The system is based on using a well-dispersed, thin, nongelling slurry with fluid-loss control. The slurry is also impermeable to gas in the cement matrix due to plugging of pore throats during the setting period (above).

In addition to reducing permeability in the presence of gas, GASBLOK slurries exhibit many other desirable properties. The main advantages are ease of design and consistent properties over a wide range of temperatures.

The lubricating action of the aqueous dispersion of the latex beads creates low-viscosity slurries. These thin slurries are beneficial for effective mud removal, since the friction pressure during placement is reduced and the critical rate for turbulent flow will be lower. If turbulent flow cannot be achieved and an effective laminar regime is chosen, it is necessary to increase the value of the rheological parameters to satisfy WELLCLEAN mud removal service criteria. Viscosification of a GASBLOK slurry is easily achieved.

Fluid loss is minimal—50 ml/30 min at the recommended latex concentration—due to the plugging of pore throats in the cement filter cake by latex particles and improved dispersion of cement grains. Setting and thickening times are straightforward and slurries exhibit rapid sets. There is no premature gelation of the slurry when the GASBLOK additive is well stabilized. The slurry remains thin until final setting. The criterion used is that the slurry should remain below 30 units of consistency for at least 70% of the thickening time. Above 250°F [121°C] bottomhole circulating temperature, a right-angle set should be easily obtained.

The tendencies for free-water development and settling of GASBLOK slurries are minimal. The formation of water channels or pockets (especially in deviated wells) is therefore greatly reduced and slurry density variations, with resulting changes in slurry properties, are avoided.

Once set, a cement must also possess good mechanical properties to withstand thermal and mechanical stresses. Poor shear bond strength may lead to formation of microannuli through which gas can migrate. GASBLOK slurries display increased tensile strength, reduced drying shrinkage, increased fracture toughness and improved adhesion or bond strength. Dowell latex slurries demonstrate all of the necessary properties to keep gas at bay. In certain cases, other cement systems used together with proper placement techniques have been as successful as, or even better than, latex in achieving particular individual properties, but none demonstrate the same complete range of desirable properties as the GASBLOK slurries.
expansion maintains a higher pore pressure in the slurry for longer than would have been the case with incompressible slurries. Foamed cement may be limited by depth because in deeper, higher pressure wells more gas is needed than is available in the cement to compensate for the chemical contraction.

In-situ gas generators are designed to maintain cement pore pressure by chemical reactions that produce gas downhole. The gas produced may be hydrogen or nitrogen depending upon the technique used.13

The principal criticism of these systems—other than concerns about the safety of those that generate hydrogen—is the inability of a gas at typical downhole pressure to achieve the 4 to 6% volumetric expansion necessary to maintain pore pressure. The volume of gas required to offset chemical shrinkage alone would be excessive at high pressure. Also, in unstabilized gas-generating systems, individual gas bubbles may coalesce and begin migrating, creating channels for formation gas to follow.

Expansive cements—Fractures occur in gelled cement according to the distribution of stress in the annulus. Eliminating this stress—and avoiding fractures—limits gas invasion. Tensile stresses build up in the gel if annular volume increases or cement volume decreases. Thus, designing cement slurries with low shrinkage and controlled fluid loss during the gelation stage, and avoiding excessive pressure fluctuations in the casing are important in preventing fractures.

Designing cement slurries that expand as they set takes this one step further. The two principal techniques for inducing expansion in oilwell cements are gas generation and crystal growth. The gas-generating technique operates on the same principle as that used for compressible cements, except that the concentration of gas-generating material is reduced. Also, expansion can occur only before the cement develops significant structural strength.

The most common way of inducing expansion is to encourage the development of ettringite—a highly hydrated form of calcium sulfoaluminate—during the hydration reaction. This is often achieved by adding gypsum or plaster of Paris to the cement powder. Ettringite increases the growth of certain expansive crystalline species within the set cement matrix. Bulk volumetric expansion is generally less than one percent.

Alternatively, oxides of certain alkaline earth metals may be hydrogen or nitrogen generated at high pressure. Also, in unstabilized gas-generating systems, individual gas bubbles may coalesce and begin migrating, creating channels for formation gas to follow.

Thixotropic cements16—During cement gelation when cement is a liquid suspension—gas bubbles can move within a cement column only if cement yield stress remains below a critical value. Designing a slurry with a rapid increase in gel strength helps trap invading gas before it can rise in the form of a bubble, preventing zonal communication or gas flow to surface. Some thixotropic slurries offer such a rapid increase in gel strength.17

There are two ways to induce thixotropic behavior in a cement slurry. The first involves creation of a microcrystalline network of mineral hydrates throughout the slurry by adding a small amount of plaster, bentonite or silicate materials. This friable and temporary microstructure supports the bulk of cement solids from an early stage in the slurry's life. The second technique employs polymers (dissolved or dispersed in the interstitial water), which are crosslinked to create a self-supporting viscous gel by chemical reaction.

The transmitted hydrostatic pressure of thixotropic systems should revert to the gradient of the interstitial water and remain as such until the setting period begins. However, at this point hydrostatic pressure may begin to decrease and gas may enter by some other mechanism.

Tough cements—Properties of set cement may also be modified by inclusion of various additives. Once again, attention has turned to polymeric latex additives that have had widespread use outside the oil field, largely because of their ability to act as tougheners. Latex-modified cements have increased tensile strength, reduced shrinkage during hydration, increased fracture toughness and improved adhesion or bonding (see “Compressive Strength Versus Toughness: A Brief Overview,” page 43).18

Predicting Gas Migration and Designing an Appropriate Solution

Armed with an understanding of the phenomena, completions engineers face the challenge of finding the right solutions (see “Gas Migration Mechanisms and Controlling Factors,” next page, bottom). Predicting likelihood of postplacement gas migration allows the design of cost-effective remedies based on the relative risk of gas migration.

Modeling gas migration is difficult because it represents a series of complex physical processes. Furthermore, it is a non-steady-state phenomenon involving varying pressure fields, changing fluid saturation and an evolving matrix structure. Heterogeneity within the cement paste or boundary effects at the casing or formation can induce events such as nonuniform gas breakthrough which are, by definition, unpredictable. Therefore, it is not possible to predict gas migration with absolute reliability. The following section describes how one company, Dowell, has developed modeling and software techniques to assess gas migration risk.19

The Dowell methodology for predicting potential gas migration began in 1989 with the GASRULE gas migration predictive slide rule. This simple slide-rule-based method uses well data, gas-zone permeability and height, gas pressure, hydrostatic conditions, mud spacer and cement characteristics, fluid volumes and mud-removal efficiency to estimate four dimensionless factors: formation factor, mud-removal factor, hydro-
Qualitative gas-migration prediction. The GASRULE slide-rule-based method of working out the optimal cementing solution has been refined and incorporated into a quantitative design approach.

Gas Migration Mechanisms and Controlling Factors

<table>
<thead>
<tr>
<th>State</th>
<th>Mechanism</th>
<th>Limiting parameters</th>
<th>Potential gas flow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscoelastic fluid</td>
<td>Bubble flow</td>
<td>Yield stress, gap width</td>
<td>10^{-9}m^3/sec</td>
</tr>
<tr>
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<td>Fracture</td>
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<tr>
<td></td>
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<td>10^{-9}m^3/sec</td>
</tr>
<tr>
<td>Elastic solid</td>
<td>Permeation</td>
<td>Fracture toughness, interfacial toughness, stress state</td>
<td>10^{-9}m^3/sec</td>
</tr>
</tbody>
</table>


16. Thixotropic gels are viscous when static, but become more fluid-like and less viscous when disturbed or moved by pumping.


19. The prediction methodology outlined is based on experiment, engineering and statistical analysis. This approach assumes gas flow through the evolving cement matrix. The model cannot predict the appearance of gas flow weeks or months after the cement job.
design and evaluation software (right). Today, the CemCADE gas-migration module assists in design and assesses alternative solutions. This methodology is a considerable improvement over the GASRULE approach, but it does retain four similar design factors: formation factor, mud-removal factor, postplacement factor and slurry-performance factor.

Formation factor—Analysis begins with characterizing all possible gas-bearing formations in terms of position, height, pressure and permeability. An accurate description of pore pressure versus depth is required to optimize hydrostatic parameters. Good descriptions of the pore pressure of other permeable layers and the fracture gradient are also required. The formation factor, indicating the risk of gas flow, is calculated from these formation parameters.

The more information about the formation that is available, the greater likelihood of a good design. Trying to understand the gas migration problem is quite difficult using only an average pore-pressure gradient for the entire openhole section.

Mud-removal factor—As mentioned, a primary goal when cementing across a gas zone is optimum mud removal. The correct application of WELLCLEAN technology is mandatory for gas-migration control. For practical purposes, good zonal isolation over a 600-ft [180-m] section above the top of a gas zone should be achieved. In the gas-migration module, information about several factors is required to determine the quality of mud removal, including:

- Mud-circulation factor—an estimate of whether enough of the mud in the well is in circulation prior to cement placement.
- WELLCLEAN factor—the factor chosen is either the turbulent or laminar flow result for a given simulation, whichever is appropriate for the well conditions and delivers the required mud removal. Time of turbulence across the zone is calculated, along with effective volume of spacer to displace the mud in laminar flow, and effective volume of cement to displace the spacer in laminar flow, as estimated from the U-tube simulation.
Pipe movement factor—assigns a positive value for pipe movement, which aids in breaking the gel strength of the mud and makes it easier to remove. This factor depends on whether reciprocation, rotation or both are used to enhance mud mobilization.

Bottom-plug factor—depends on the number of bottom plugs used to reduce the degree of contamination occurring as fluids are circulated.

Fluids-compatibility factor—relates to possible chemical interaction between various fluids.

The final mud-removal factor is then computed by summing these five factors—the greater the final value, the better the anticipated result.

Postplacement factor—Postplacement analysis is used to evaluate the severity of a potential gas migration problem and to quantify the influence of simple solutions such as applying annular pressure. As previously discussed, gas migration is generally caused by a loss of hydrostatic pressure. First-level understanding of this may be derived from gelation alone.

To characterize gelation, the notion of wall shear stress (WSS) has been introduced (see "How Gas Gets into the Annulus, page 39). As WSS increases, annular hydrostatic pressure falls. When hydrostatic pressure equals formation gas pressure, WSS is termed “critical” WSS (CWSS). Further increase in WSS beyond this critical value will allow gas to enter the annulus. WSS depends on parameters such as formation gas pressure, openhole diameter, and density and position of fluids. It is also sensitive to any extra annular pressure, the presence of external casing packers or techniques like two-stage cementing that may sometimes be employed to improve gas control.

CemCADE software calculates WSS and assesses how use of hydrostatic modifiers—such as ECPs—may be adjusted to maximize the critical WSS, delaying gas entry and allowing more time for cement to harden uninvaded. However, the calculation does not take into account possible fluid loss that may accelerate annular pressure decrease.

Slurry-performance factor—Once gas enters the cement column, it may migrate to a point of lower pressure. Resistance to gas depends on slurry composition. For every slurry there is a minimum wall shear stress (MWSS) above which gas can no longer migrate. The MWSS depends mainly on the chemical composition of the slurry as well as bottomhole static temperature.

For every design there is a critical range for WSS and, therefore, a critical time period during which gas can migrate in the slurry. This period extends from the time at which the slurry reaches critical WSS to the time it becomes impermeable to gas. Optimizing a design consists of reducing this time period by increasing critical WSS, decreasing MWSS or shortening the time to go from the CWSS to the MWSS.

The two parameters used by the Dowell CemCADE system to calculate the slurry-performance factor are transition time and fluid loss. The faster the slurry develops impermeability to gas, the lower the probability that gas migration will occur. The measure of the evolution of the relative permeability of a cement slurry to gas during the hydration period determines whether a cement slurry can control gas. The rate of cement-slurry permeability decline is difficult to measure. But it is possible to correlate permeability decline to the rate of change in consistency of a cement slurry during an API thickening time test—that is, the transition time.

During cement hydration, a major cause of pore-pressure loss is the loss of fluid to surrounding formations. The propensity for gas to percolate may thus be related to the fluid-loss potential of the slurry. Transition time and fluid loss have been incorporated into a single term, the slurry-performance factor.

Gas-migration factor—The formation, mud-removal, postplacement and slurry-performance factors are then linearly combined to give the final index or gas-migration factor. Evaluation of the risk associated with a given design is based on the gas-migration factor compared to a scale ranging from “very critical” to “very low” risk of migration.

Looking Forward to Further Change

Every completions engineer knows that gas migration is a complex problem. Successful control requires systematically addressing the gamut of factors that affect final job quality. Attempting to prevent gas migration by addressing a single factor chosen from the list of possible chemical and mechanical events will inevitably result in failure.

This year, CemCADE design software will become available on a PC platform. The transition from rules-of-thumb governing choice of solution through a slide-rule system of assessing gas migration to a computer-based design system will be complete. Some of the advances and technology that have been described contribute not only to combating gas migration, but also to improving the quality of all critical cement operations. Mud removal, correct choice of slurry type and accurate mixing technology are key elements in the evolving world of cementing design and execution. —CF